2009 Neutrino Summer School

Neutrino History

accelerator, atmospheric, reactor and solar experiments

... and some lessons learned

Karsten M. Heeger

University of Wisconsin

- **History of Neutrino Physics**
  - *- how did we learn what we know today?*
  - *- from saving energy conservation to discovering physics beyond the Standard Model*

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  - how did we make the discoveries?

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- **Historical Lessons**
  - *how did we make the discoveries?*

- **Future Efforts**
  - *from discoveries to precision studies, picking the best tools at hand*
  - *where will neutrino physics go in the future?*
  - *neutrinos in particle/astrophysics?*

A disclaimer

History of neutrino physics in ~1 hr?

I will be selective. Apologies to all experiments and results I cannot show.

I will draw heavily on my own personal experience (SNO, KamLAND, reactor neutrinos, $0\nu\beta\beta$)

History of Neutrino Physics

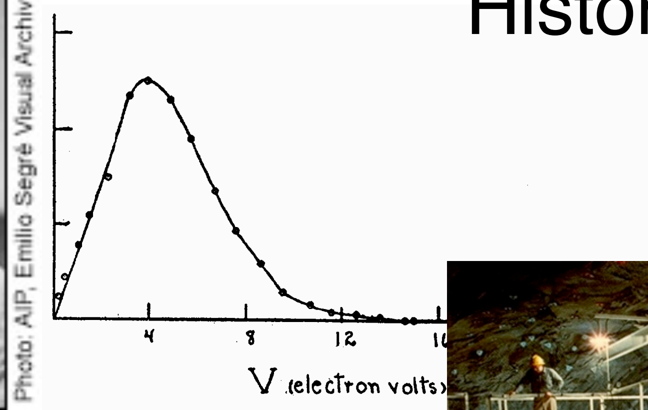
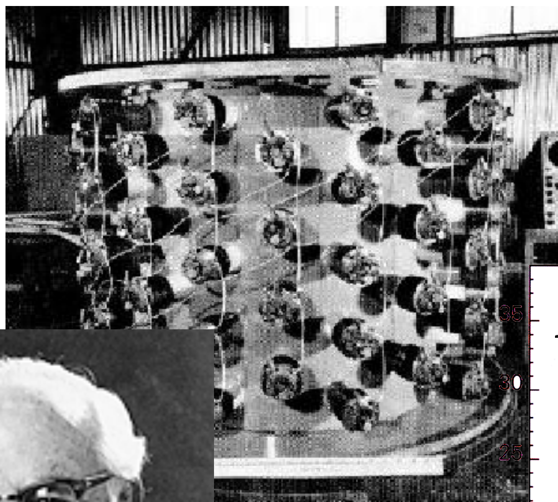
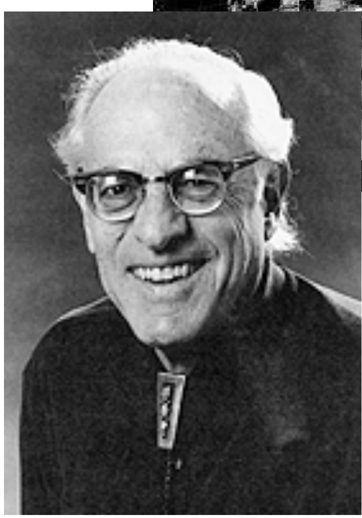
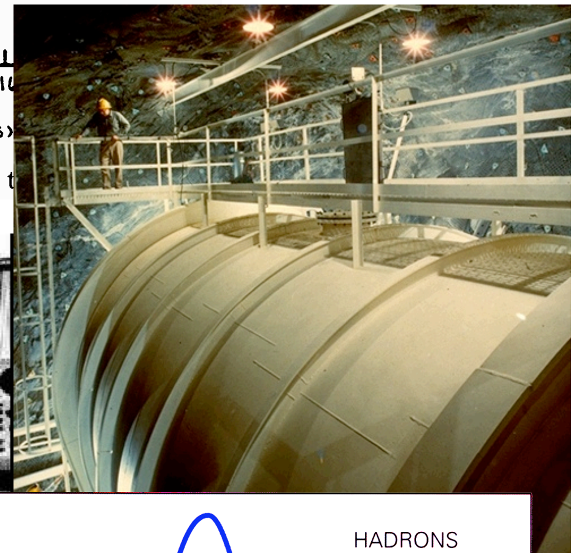
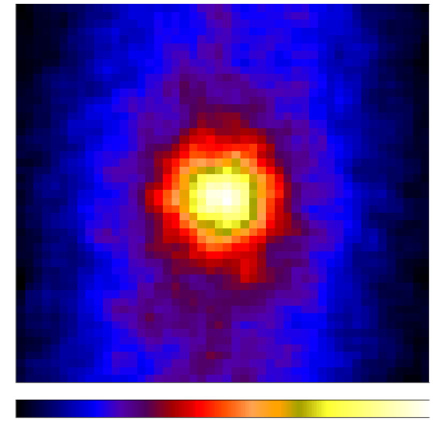


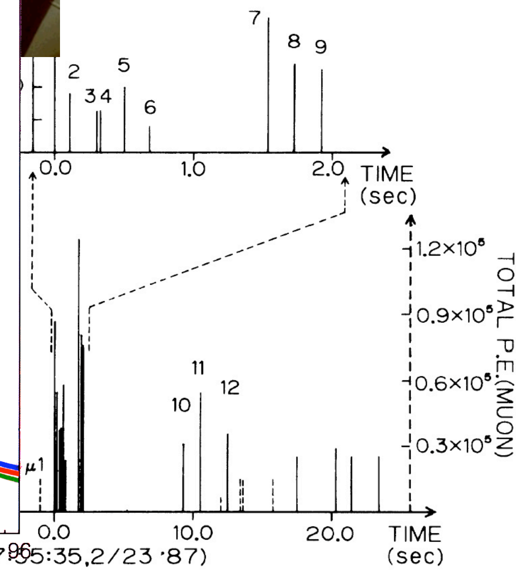
FIG. 5. Energy distribution curve of t

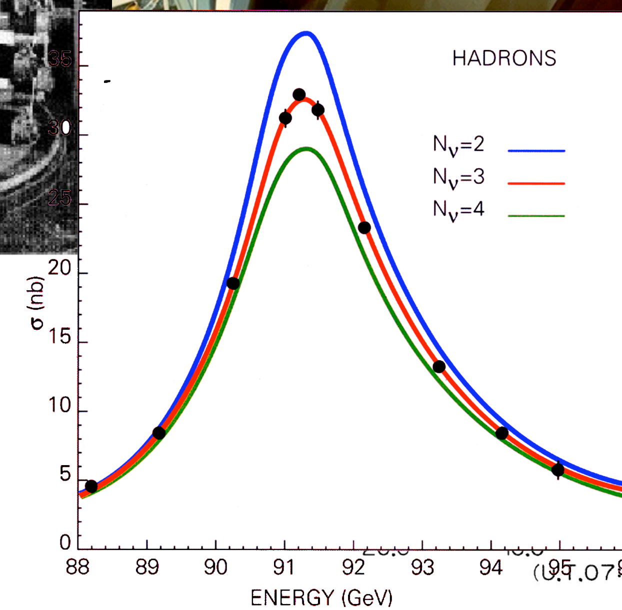












Continous Beta-Decay Spectrum

1914 Chadwick

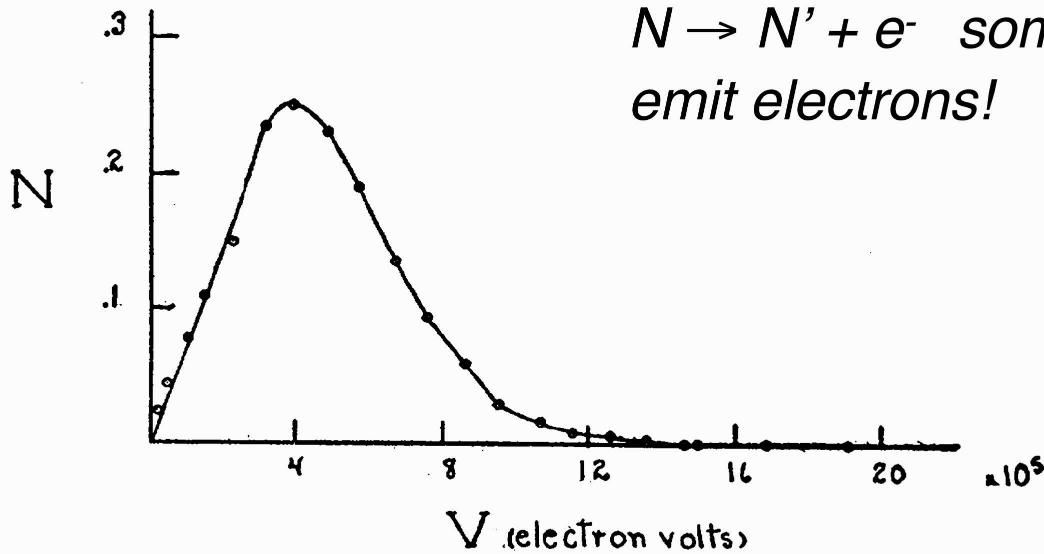


FIG. 5. Energy distribution curve of the beta-rays.

$N \rightarrow N' + e^-$ some nuclei emit electrons!

Bohr: "*At the present stage of atomic theory, however, we may say that we have no argument, either empirical or theoretical, for upholding the energy principle in the case of β-ray disintegrations*".

Postulate of the Neutrino

1930

Photo: AIP, Emilio Segrè Visual Archives

Wolfgang Pauli

Abschrift/15.12.56 PM

Offener Brief an die Gruppe der Radioaktiven bei der
Gauvereins-Tagung zu Tübingen.

schrift

ysikalisches Institut
r Eidg. Technischen Hochschule — Zürich, 4. Dez. 1930
irich — Gloriastrasse

Liebe Radioaktive Damen und Herren,

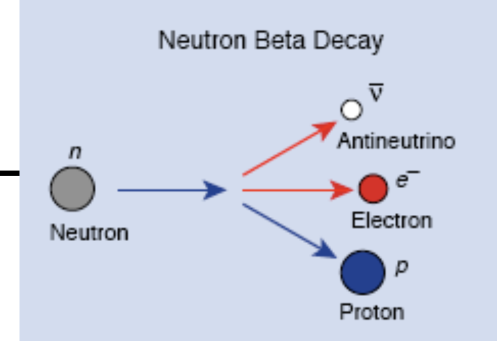
Wie der Ueberbringer dieser Zeilen, den ich huldvollst
zuhören bitte, Ihnen des näheren auseinandersetzen wird, bin ich
gesichts der "falschen" Statistik der N- und Li-6 Kerne, sowie
s kontinuierlichen beta-Spektrums auf einen verzweifelten Ausweg
rfallen um den "Wechselsatz" (1) der Statistik und den Energiesatz
retten. Nämlich die Möglichkeit, es könnten elektrisch neutrale
Teilchen, die ich Neutronen nennen will, in den Kernen existieren,
welche den Spin 1/2 haben und das Ausschliessungsprinzip befolgen und
sich von Lichtquanten ausserdem noch dadurch unterscheiden, dass sie
nicht mit Lichtgeschwindigkeit laufen. Die Masse der Neutronen
müsste von derselben Grossenordnung wie die Elektronenmasse sein und
jedenfalls nicht grösser als 0,01 Protonenmasse.- Das kontinuierliche
beta- Spektrum wäre dann verständlich unter der Annahme, dass beim
beta-Zerfall mit dem Elektron jeweils noch ein Neutron emittiert
wird, derart, dass die Summe der Energien von Neutron und Elektron
konstant ist.

Pauli proposed that an undetectable particle shared the energy of beta decay with the emitted electron.

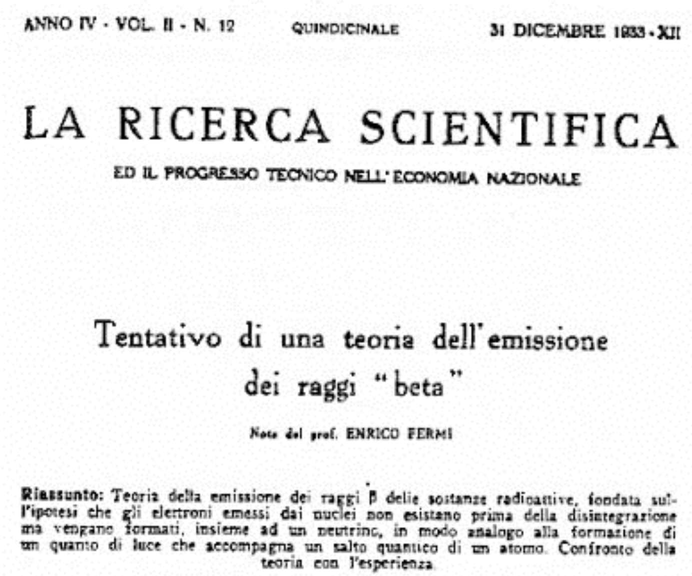
"I have done something very bad today by proposing a particle that cannot be detected; it is something that no theorist should ever do."

- Wolfgang Pauli

Fermi’s Theory of Beta Decay



1933



ANNO IV - VOL. II - N. 12 QUINDICINALE 31 DICEMBRE 1933 - XII

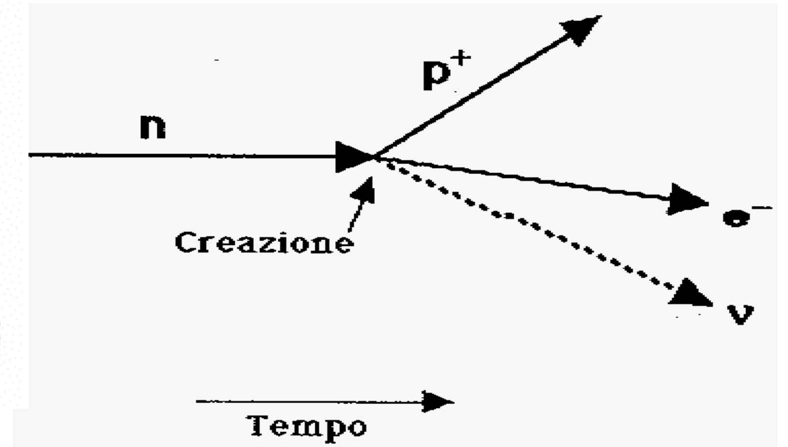
LA RICERCA SCIENTIFICA

ED IL PROGRESSO TECNICO NELL' ECONOMIA NAZIONALE

Tentativo di una teoria dell'emissione dei raggi “beta”

Nota del prof. ENRICO FERMI

Riassunto: Teoria della emissione dei raggi β delle sostanze radioattive, fondata sull'ipotesi che gli elettroni emessi dai nuclei non esistano prima della disintegrazione ma vengano formati, insieme ad un neutrino, in modo analogo alla formazione di un quanto di luce che accompagna un salto quantico di un atomo. Confronto della teoria con l'esperienza.



Enrico Fermi
Univ. of Chicago

Experiment: $M_n c^2 \neq E_p + E_e$

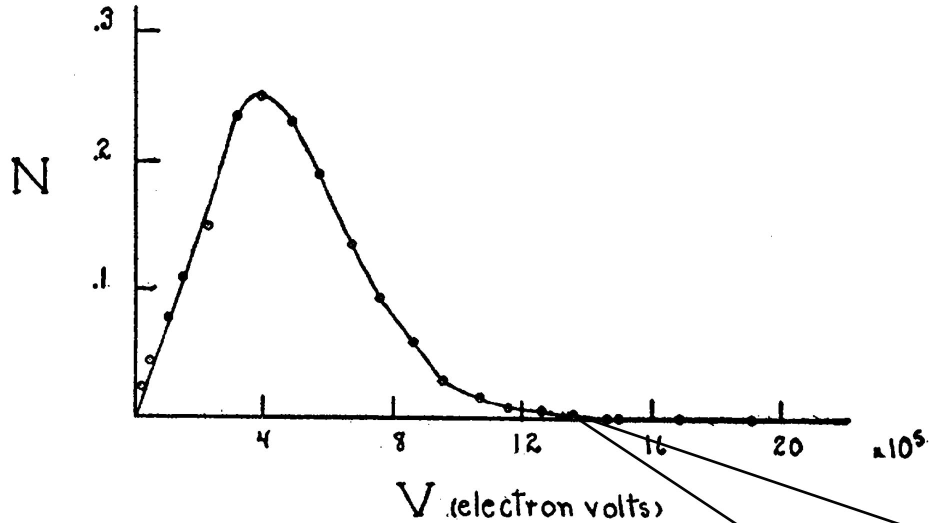
Conjecture: $M_n c^2 = E_p + E_e + E_\nu$

Fermi’s Theory of beta decay based on Pauli’s Letter of Regrets

Consistency requires that E_ν is not observable!

Fermi’s theory still stands (parity violation added in the 50s).

Fermi's Idea for Measuring m_ν



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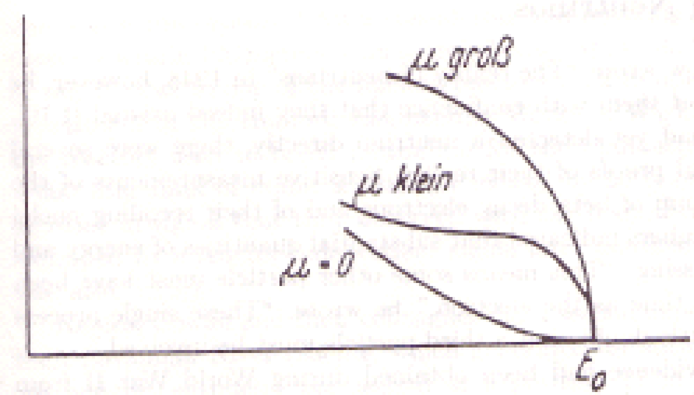
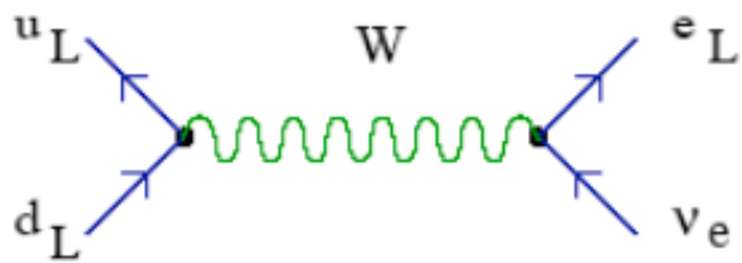


Fig. 1.2. Graph from Fermi's famous paper on the theory of beta decay, showing how the shape of the emitted electron's energy spectrum varies with neutrino mass

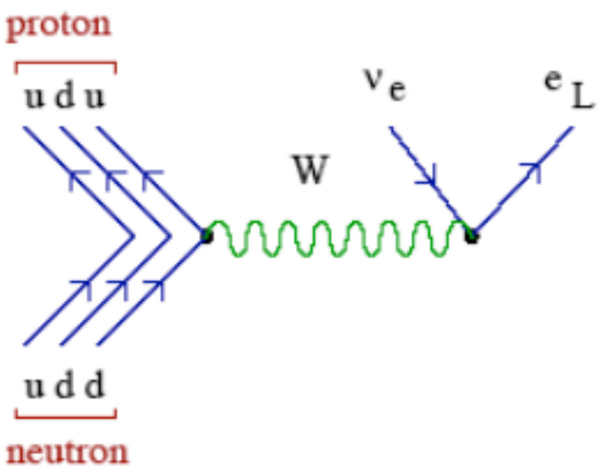
Weak Interactions in the Standard Model

The weak gauge bosons $W^{\pm}$ act on left-handed doublets

(charged-current interaction)



β-decay



Since m_w=80.4 GeV >> m_p decay is governed by Fermi coupling G_F

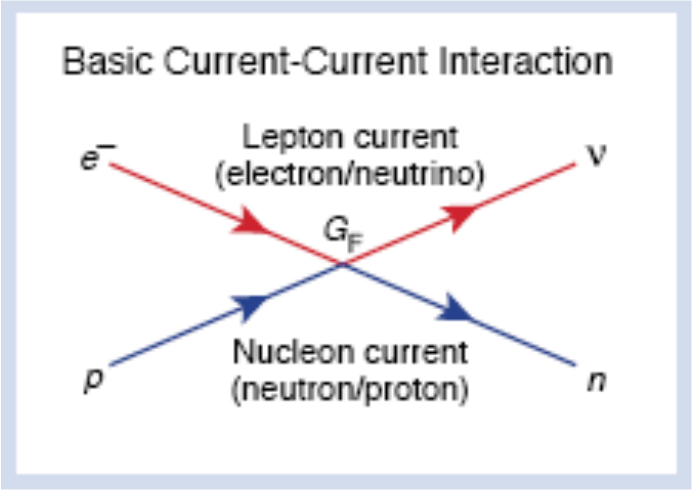
Fermi coupling

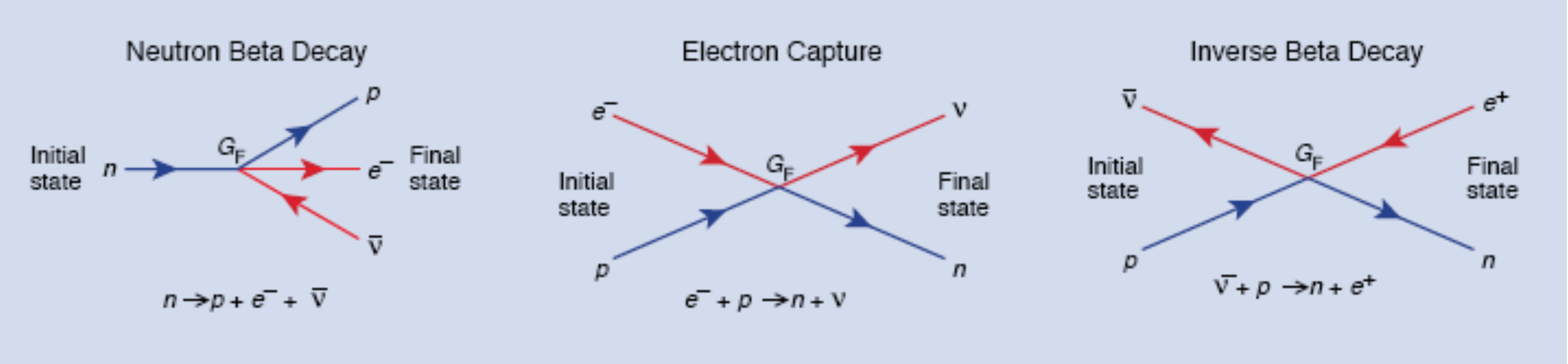
$$\frac{G_F}{\sqrt{2}} = \frac{{g_2}^2}{8{m_W}^2}$$

g_2= W gauge coupling

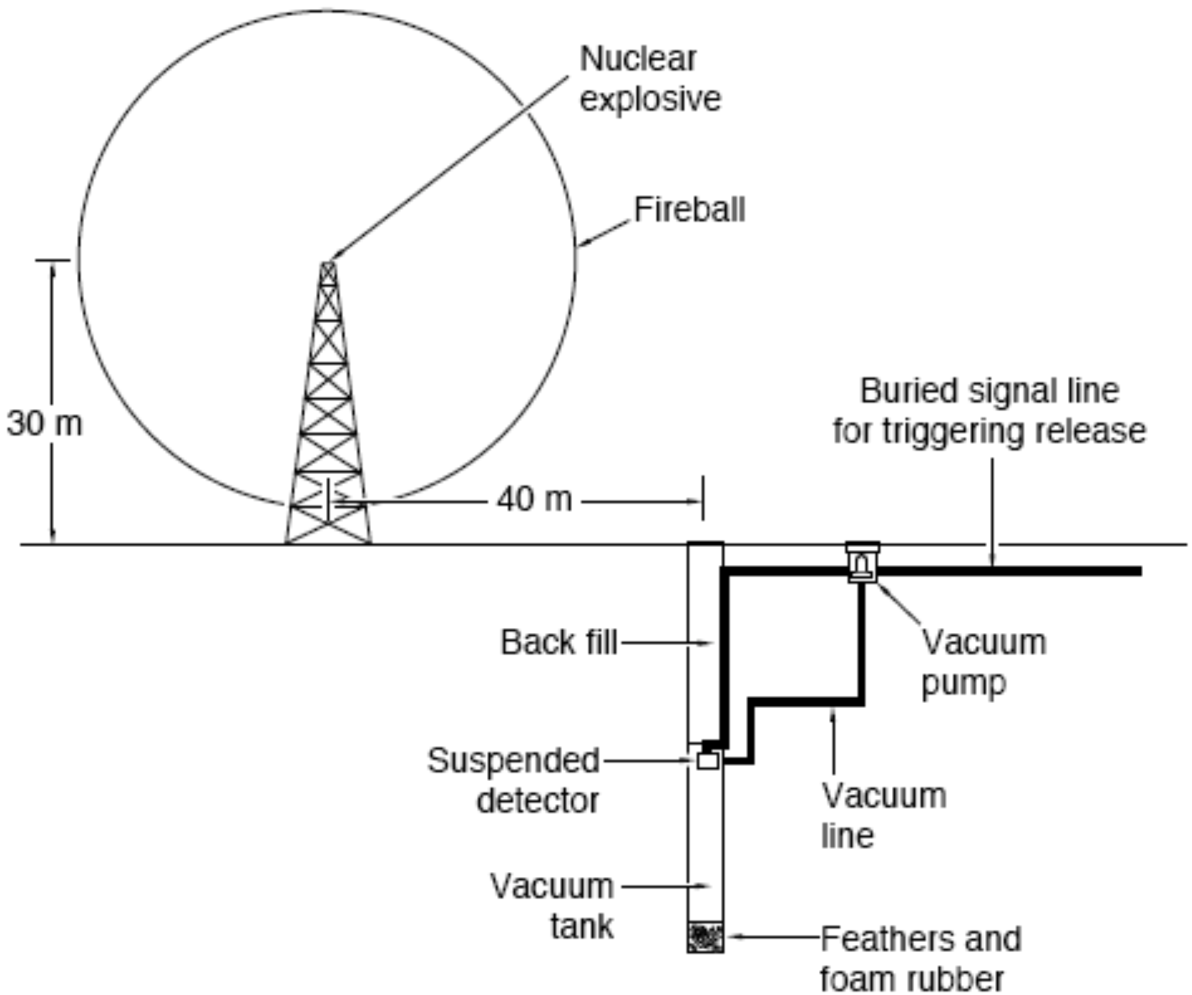
Weinberg angle $\frac{e}{g_2} = \sin\theta_W = 0.48$

Crossing Symmetry

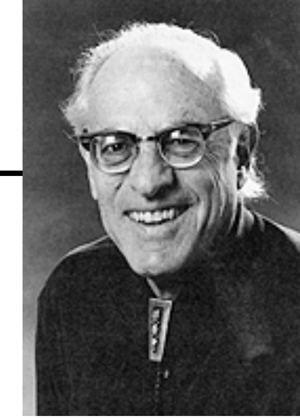


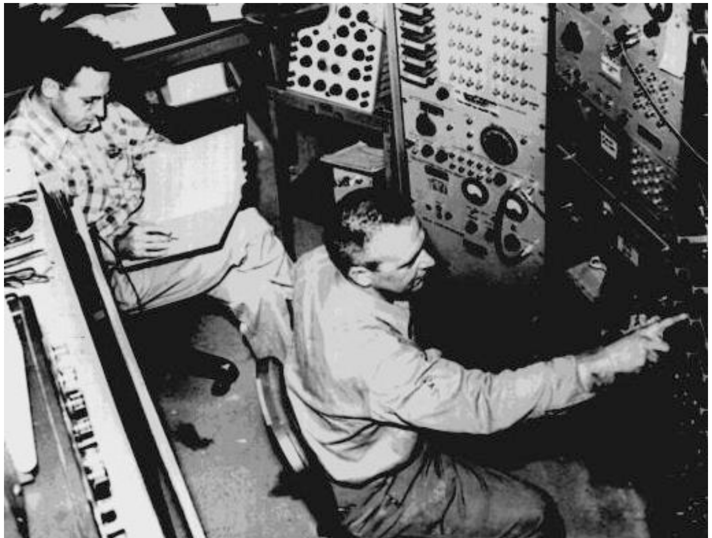


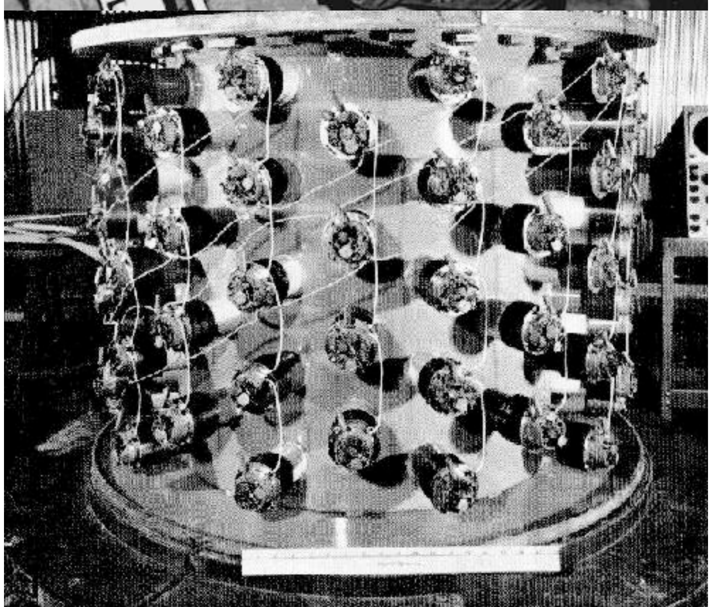
First Proposal For Direct Detection of Neutrino



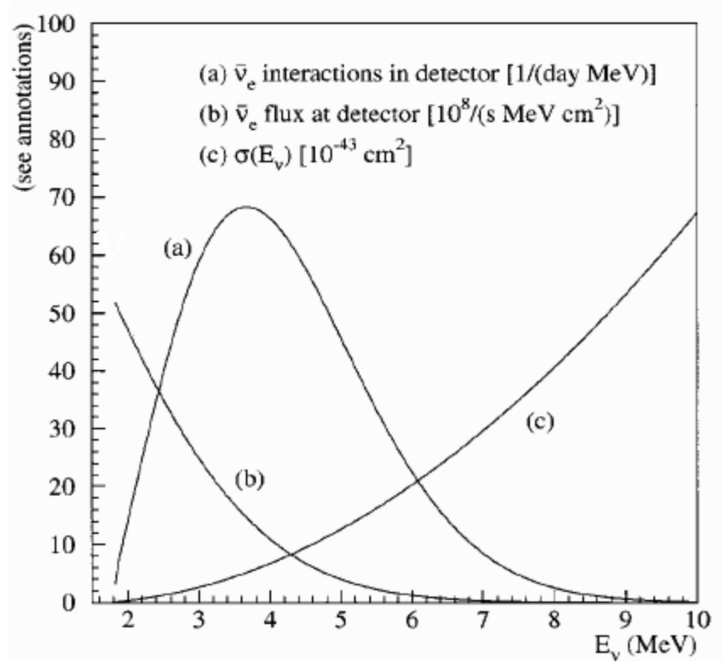
First Antineutrino Detector



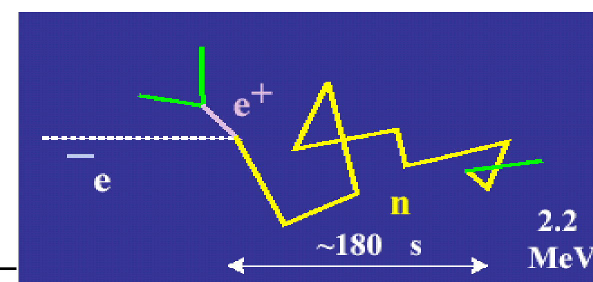




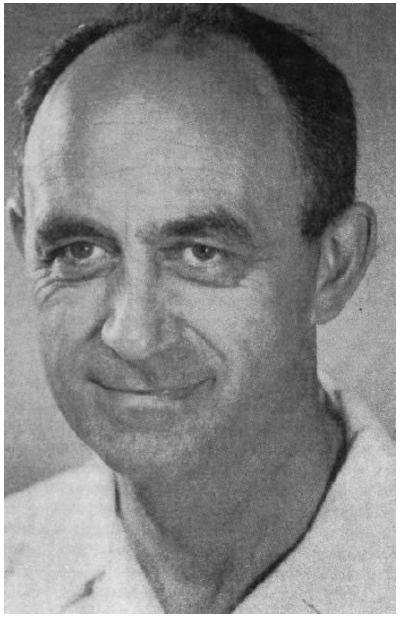
Reines and Cowan 1956



$$\overline{\nu}_e + p \rightarrow e^+ + n$$



Enrico Fermi and the Neutrino



Enrico Fermi proposes "neutrino" as the name for Pauli's postulated particle.

He formulates a quantitative theory of weak particle interactions in which the neutrino plays an integral part.

THE UNIVERSITY OF CHICAGO
CHICAGO 37 · ILLINOIS
INSTITUTE FOR NUCLEAR STUDIES

October 8, 1952

Dr. Fred Reines
Los Alamos Scientific Laboratory
P.O. Box 1663
Los Alamos, New Mexico

Dear Fred:

Thank you for your letter of October 4th by Clyde Cowan and yourself. I was very much interested in your new plan for the detection of the neutrino. Certainly your new method should be much simpler to carry out and have the great advantage that the measurement can be repeated any number of times. I shall be very interested in seeing how your 10 cubic foot scintillation counter is going to work, but I do not know of any reason why it should not.

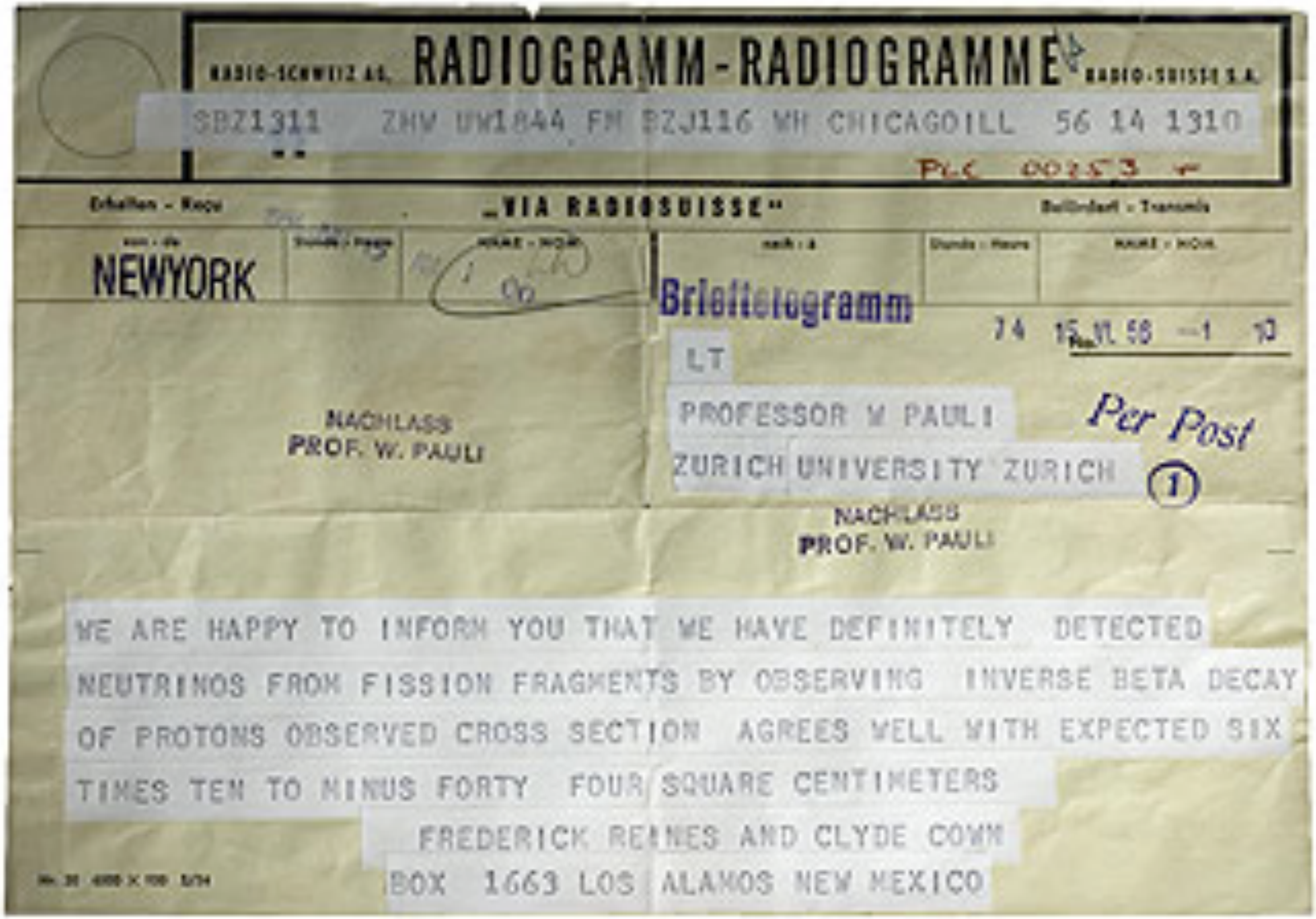
Good luck.

Sincerely yours,
Enrico
Enrico Fermi

EF:vr

Reines-Cowan Announcement

1956



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PROFESSOR W PAULI

ZURICH UNIVERSITY ZURICH

Per Post

NACHLASS PROF. W. PAULI

NACHLASS PROF. W. PAULI

WE ARE HAPPY TO INFORM YOU THAT WE HAVE DEFINITELY DETECTED NEUTRINOS FROM FISSION FRAGMENTS BY OBSERVING INVERSE BETA DECAY OF PROTONS OBSERVED CROSS SECTION AGREES WELL WITH EXPECTED SIX TIMES TEN TO MINUS FORTY FOUR SQUARE CENTIMETERS

FREDERICK REINES AND CLYDE COWN

BOX 1663 LOS ALAMOS NEW MEXICO

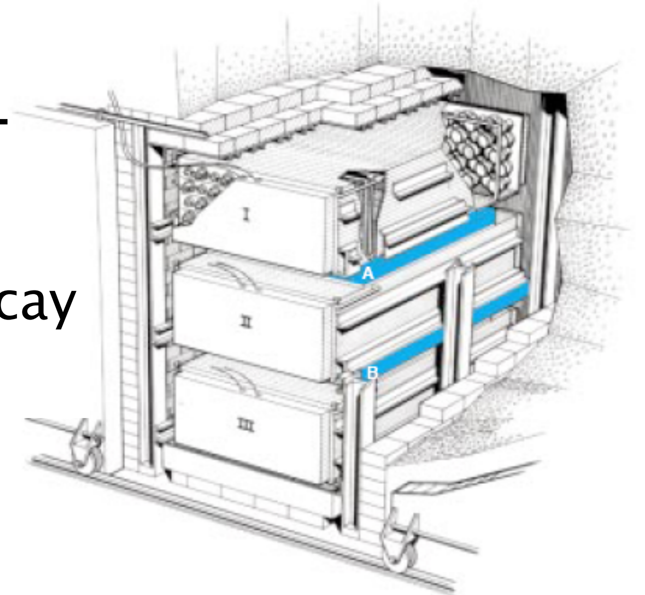
Observation of the Free Antineutrino

1959 The Savannah River Detector - A new design

Second version of Reines' experiment worked!

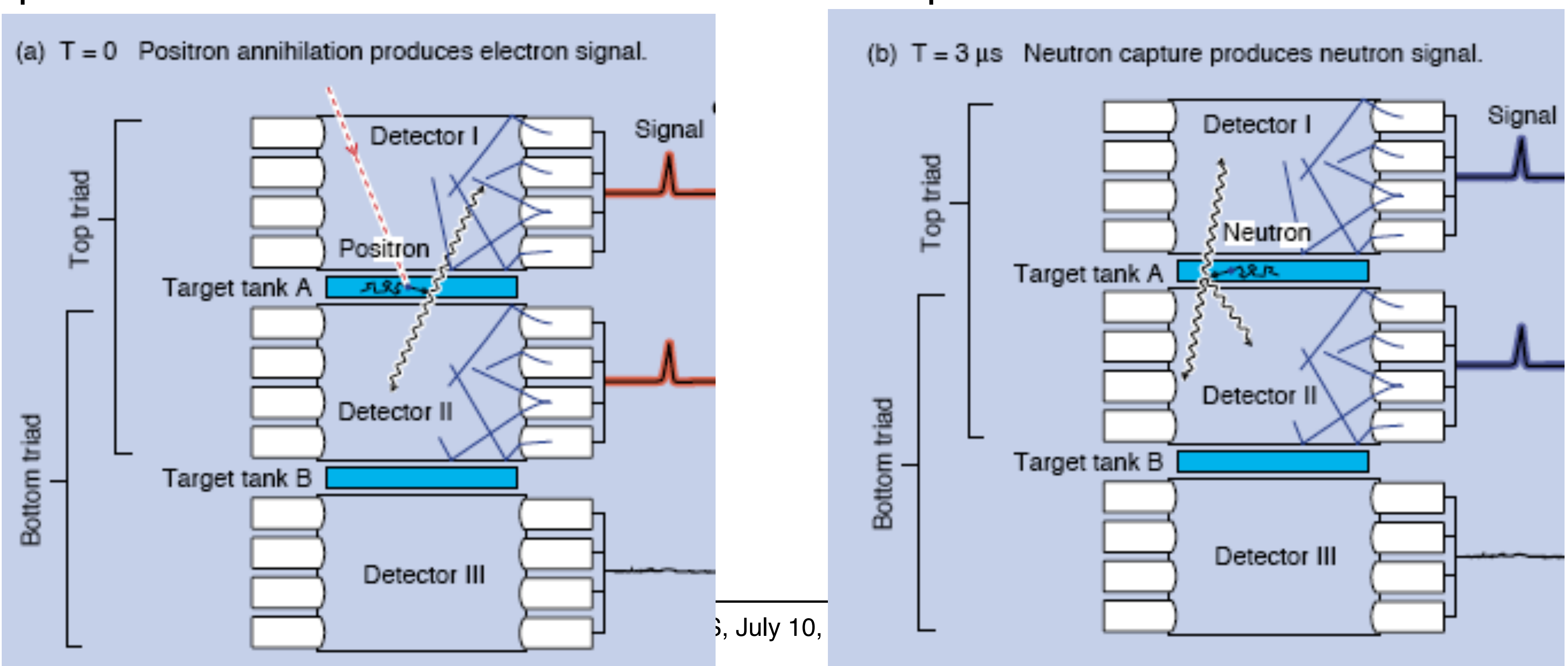
inverse beta decay

$\bar{\nu}_e + p \rightarrow e^+ + n$



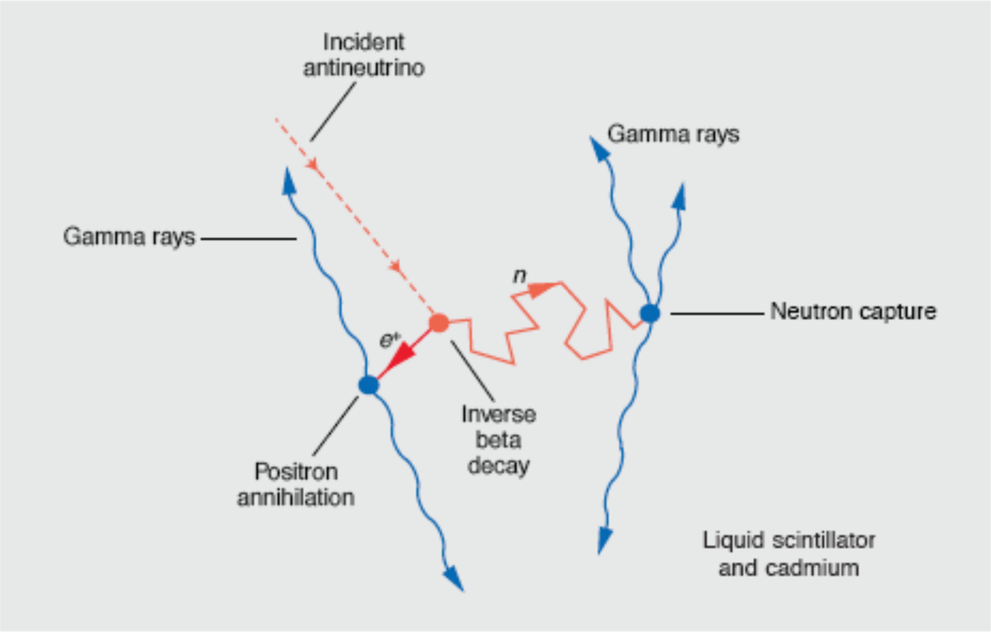
positron annihilation

n capture

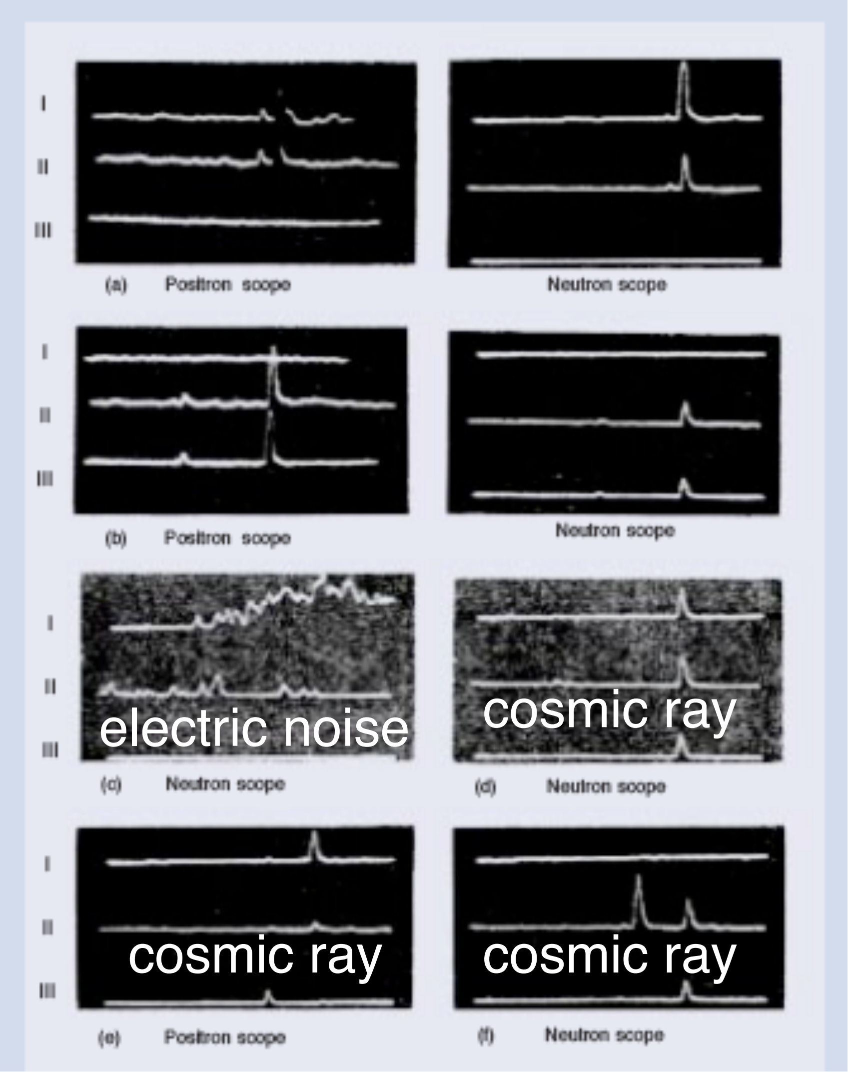


Reines-Cowan Experiment

coincidence event signature



event signal



Early Neutrino Oscillation Searches

New neutrino physics such as oscillations?

In 1960's Pontecorvo contemplates $\nu - \bar{\nu}$ oscillation and suggests that if lepton number is not conserved ν_e could change into ν_μ.

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Бруно Понтекорво

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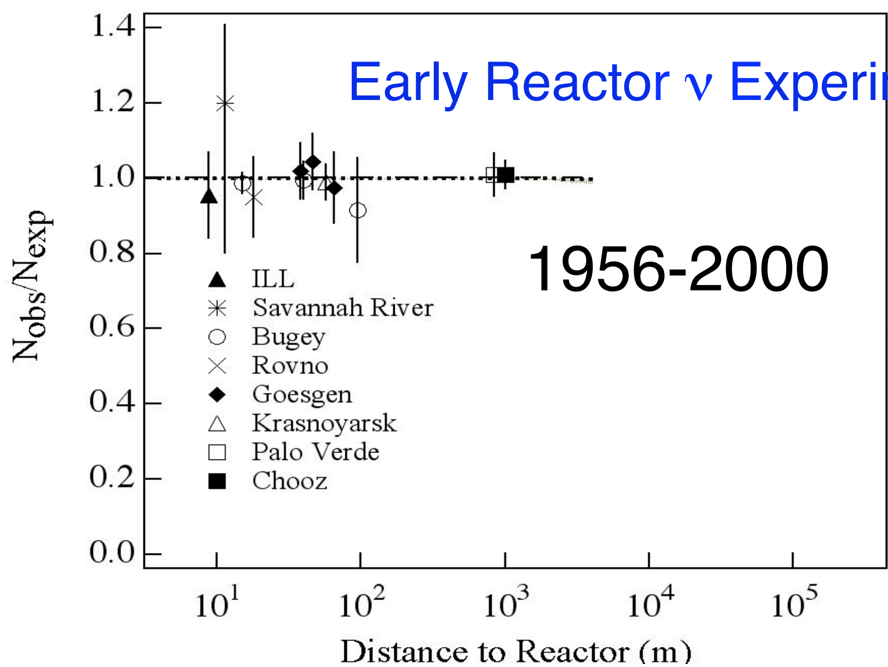

Early Reactor ν Experiments

1956-2000

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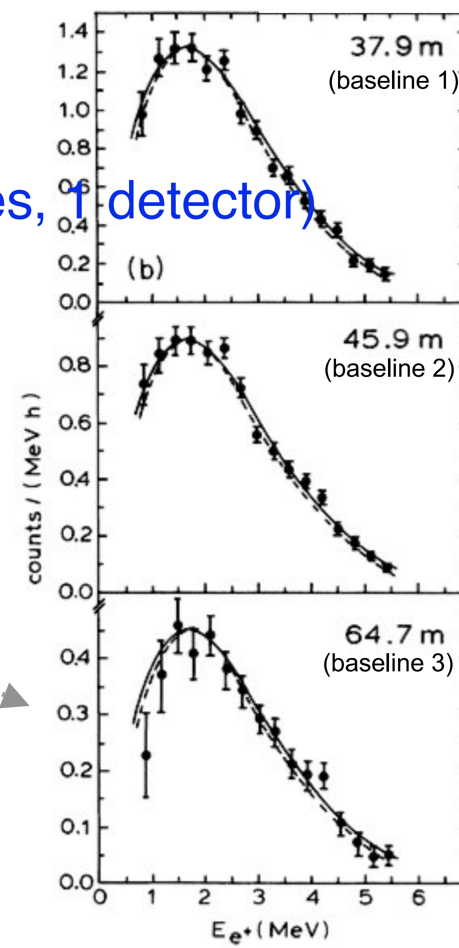
Goesgen

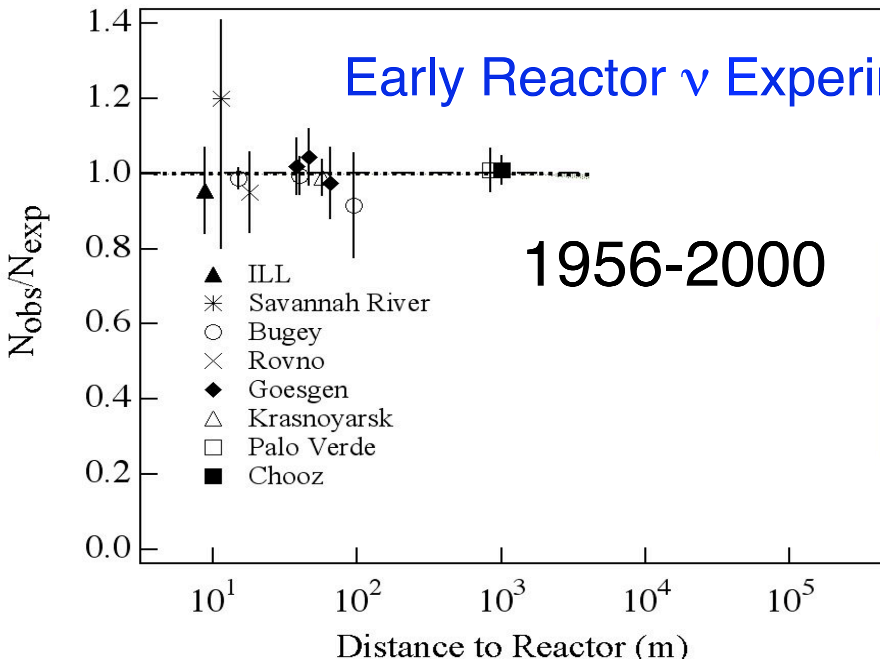
(3 baselines, 1 detector)



Phys Rev D **34**, 2621 (1986)

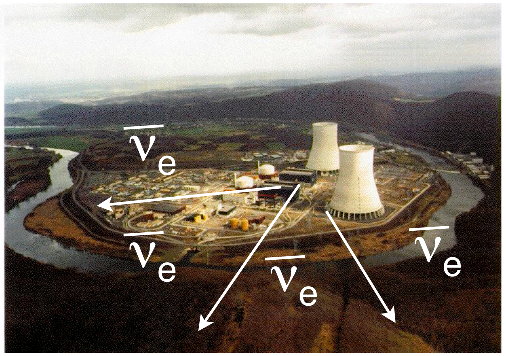
Early Reactor ν Experiments

1956-2000

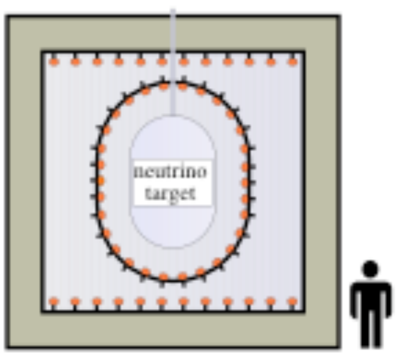


Neutrino Oscillation Search with Reactor Antineutrinos

Oscillation Searches at Chooz + Palo Verde: $\overline{\nu}_e \rightarrow \overline{\nu}_x$



Distance: 1km



Absolute measurement with 1 detector

detector size: several tons

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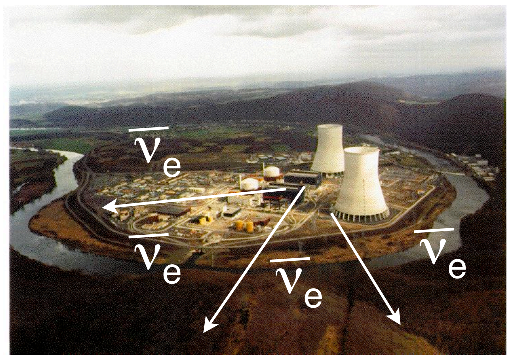

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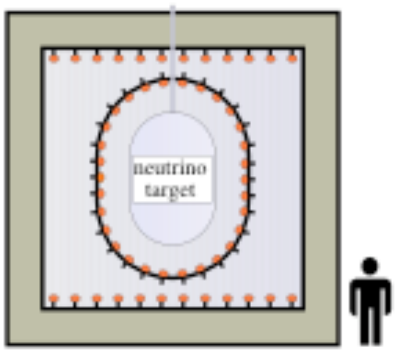
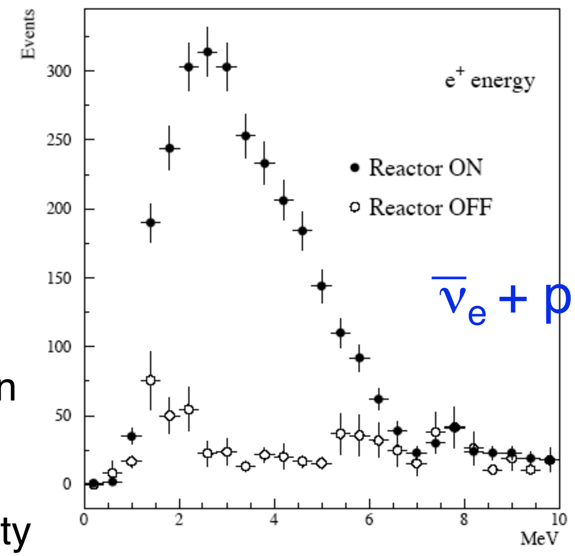


~3000 events in 335 days

2.7% uncertainty



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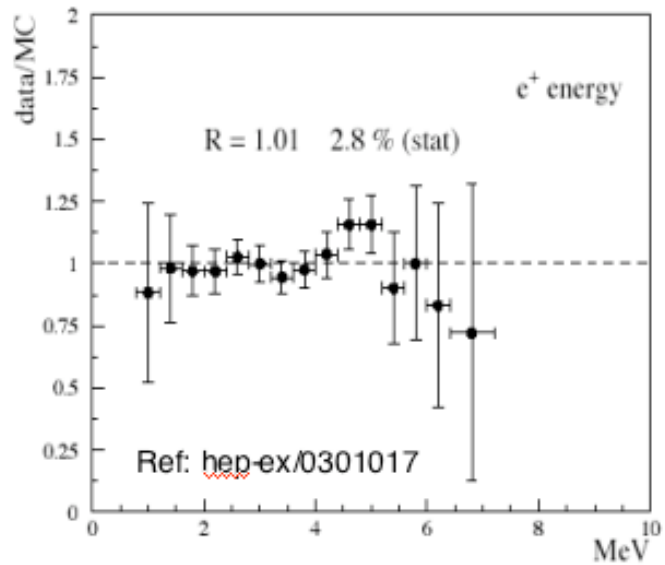

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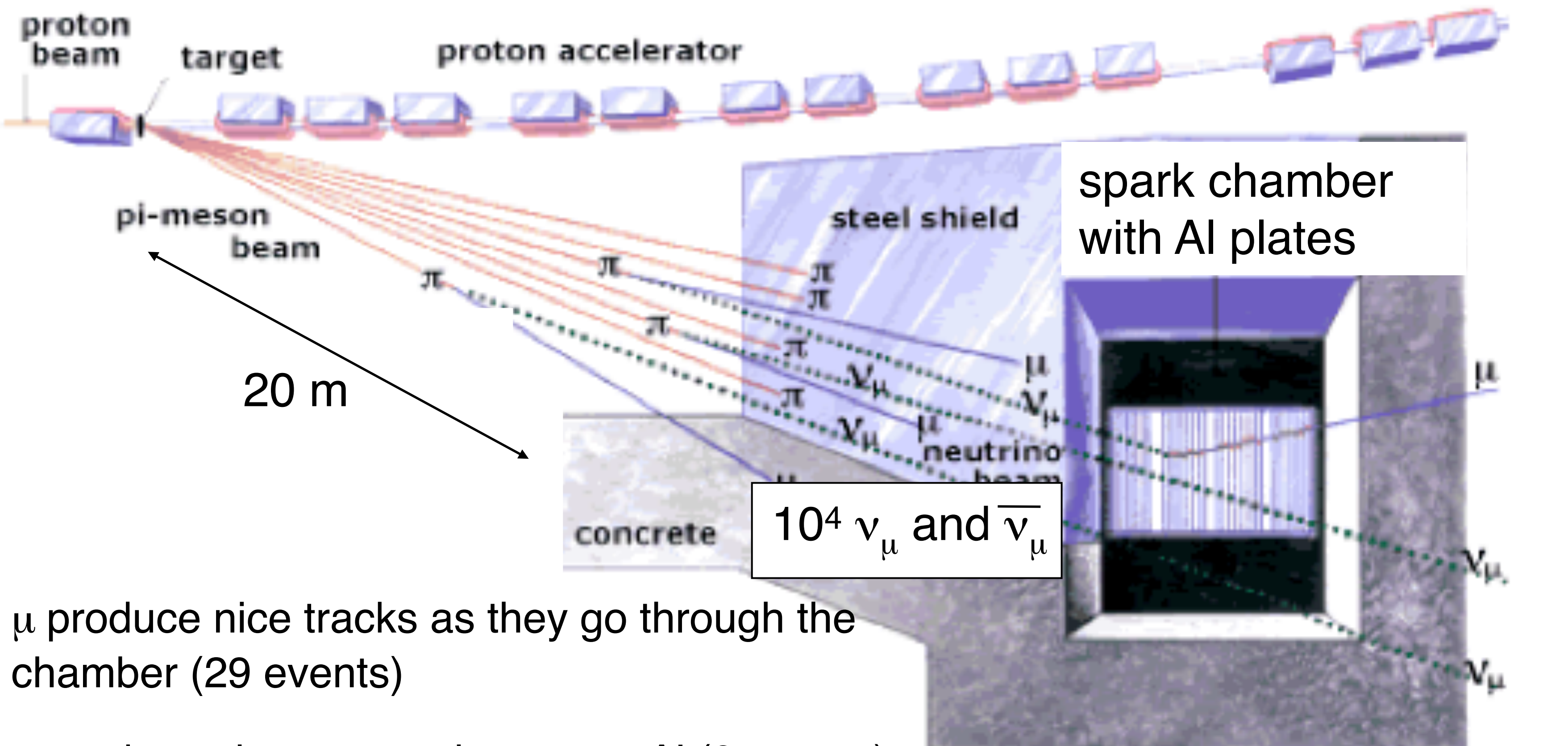
Discovery of Muon Neutrino

1962

$$
\begin{aligned}
\bar{\nu}_\mu &+ p \rightarrow n + \mu^+ \\
\nu_\mu &+ n \rightarrow p + \mu^-
\end{aligned}
$$

Lederman, Schwartz, Steinberger



μ produce nice tracks as they go through the chamber (29 events)

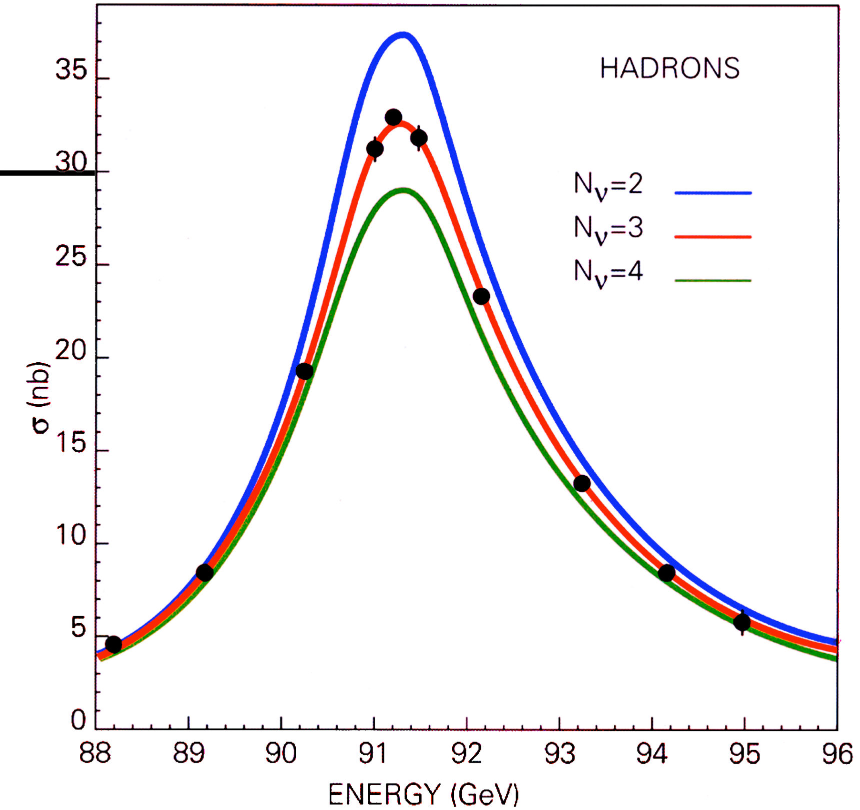
e produce showers as they cross Al (0 events)

Number of Active Neutrinos

Precision studies of Z-line shape, determine number of active light neutrinos

Each separate $(\nu_{l_i})_L$ adds to total Z-width.

$$Z^o \to q\bar{q}, l\bar{l} \qquad N_\nu = \frac{\Gamma_{\rm inv}}{\Gamma_\ell}\left(\frac{\Gamma_\ell}{\Gamma_\nu}\right)_{\rm SM}$$



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which argues strongly for only having 3 generations

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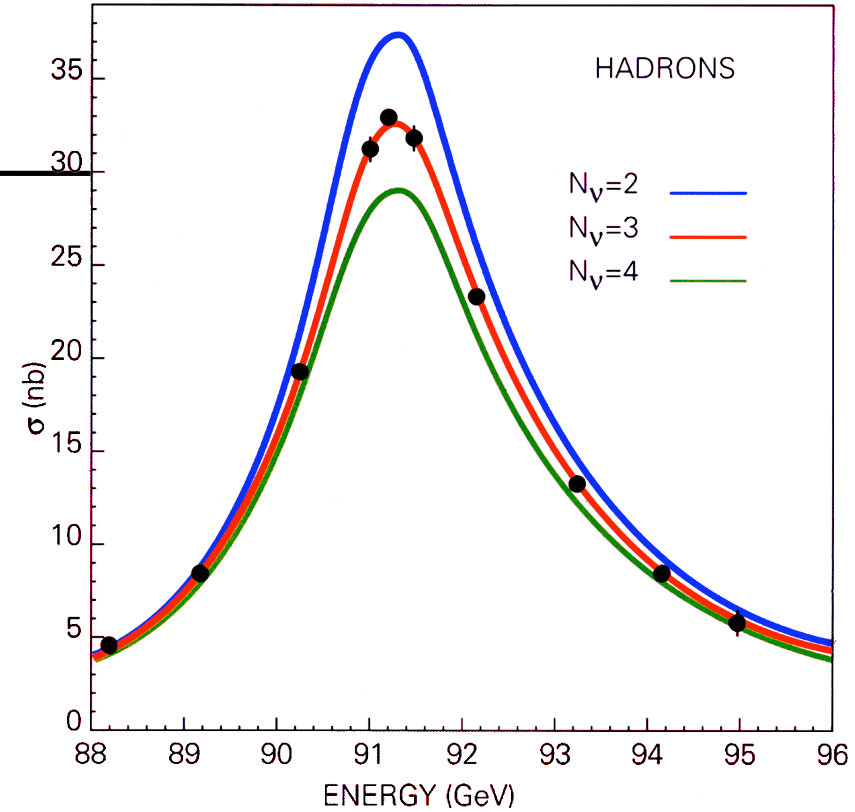

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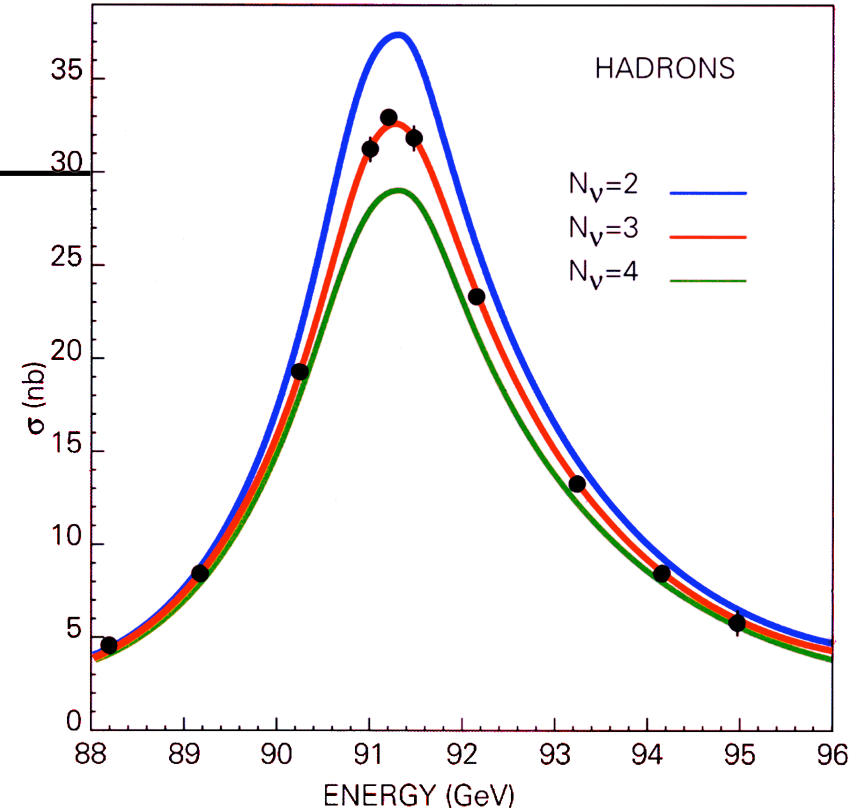

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$1.2 < N_\nu^{\rm eff} < 3.3$ [99% CL]

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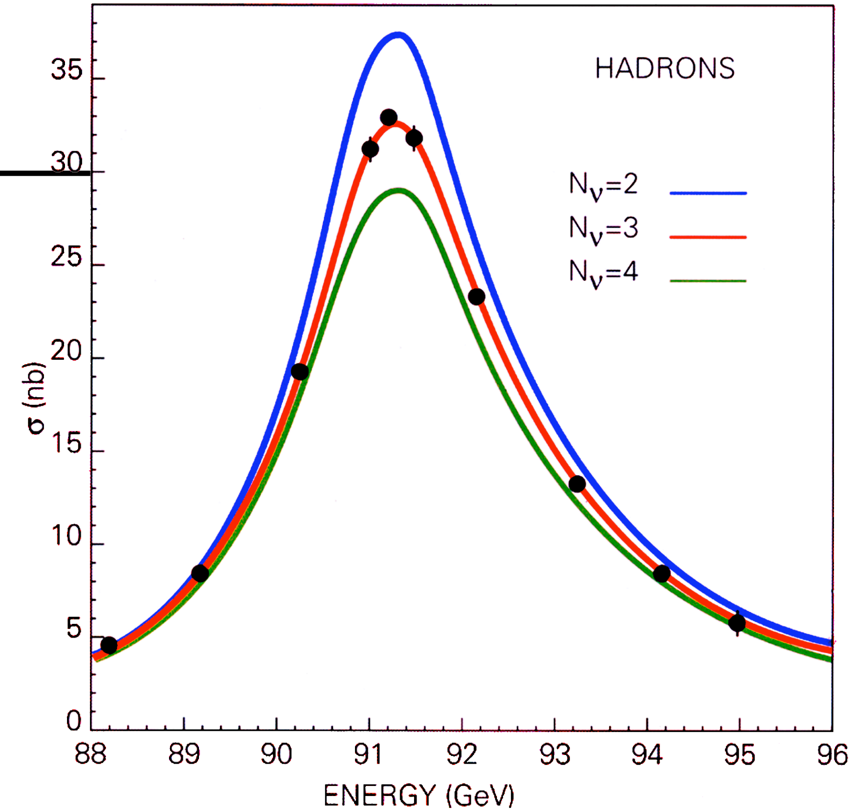

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Search for tau Neutrino

Discovery of τ lepton at SLAC (Martin Pearl, 1975)

$\rightarrow$ there should be a corresponding neutrino.

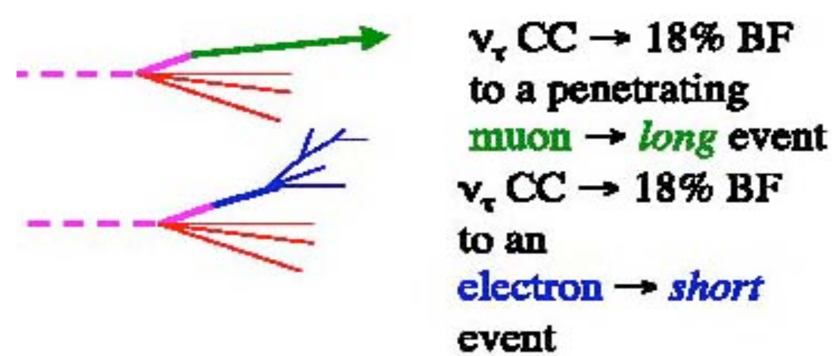
In 1989, indirect evidence for the existence of ν_τ in measurement of Z-width

$\rightarrow$ no one had directly observed the tau neutrino.

The tau neutrino interact and form a tau that has an 18% probability of decaying to

- a muon and two neutrinos (long event)
- an electron and two neutrinos (short event)

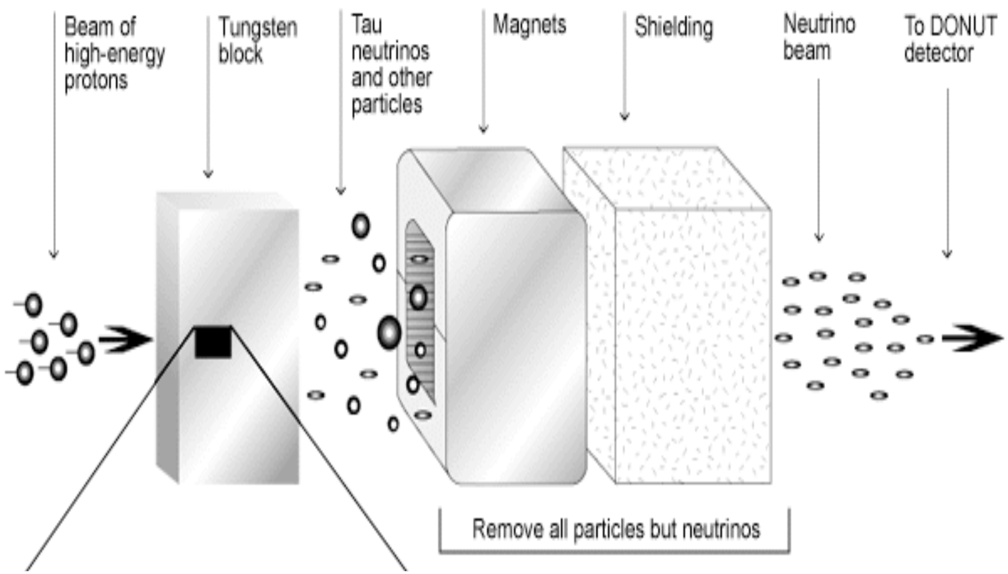
86% of all tau decays involve only 1 charged particle (a kink) which is the particle physicists are looking for in DONUT experiment



Discovery of tau Neutrino

2000

An 800 GeV beam of protons from the TeVatron collides with a block of tungsten



D_s decay into τ and ν_τ neutrino

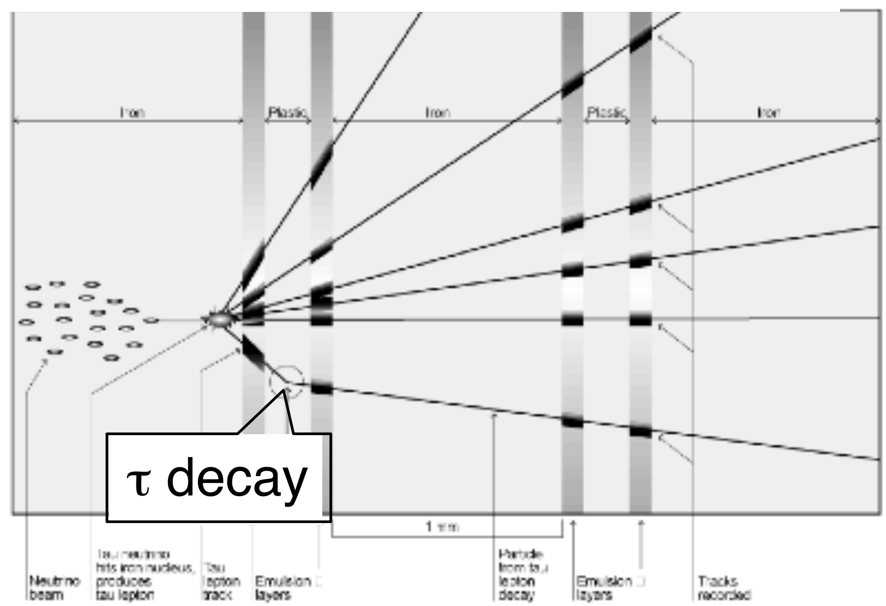
$$D_s \rightarrow \nu_\tau + \tau$$
$$\tau \rightarrow \nu_\tau + X$$

Experimental Challenges:

- Very short lifetime of the τ.
- ν_τ is extremely non-interacting

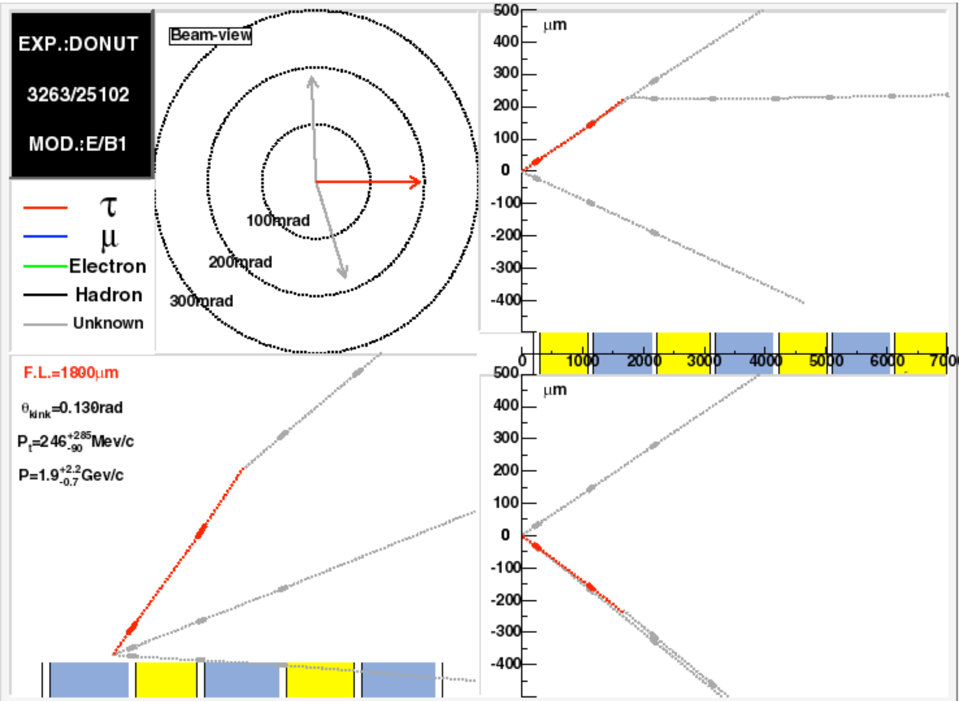
(detector must have a very fine resolution).

Detecting a τ Neutrino

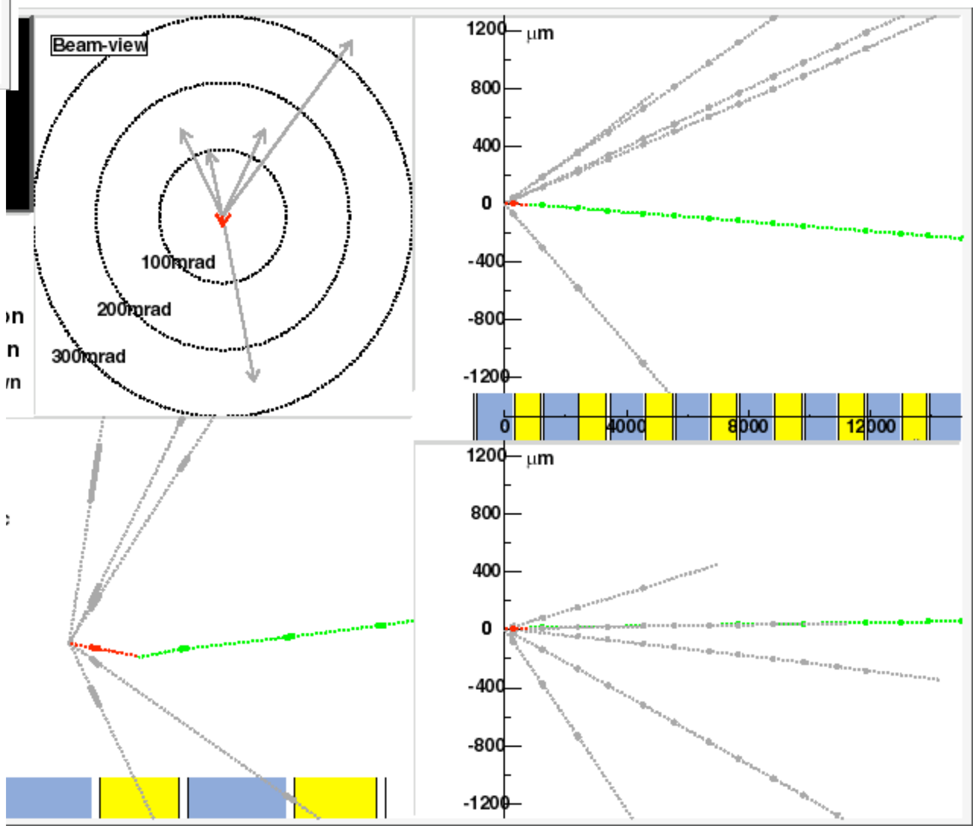


6,000,000 candidate events on tape

4 clean tau events

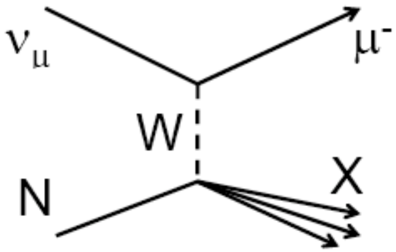


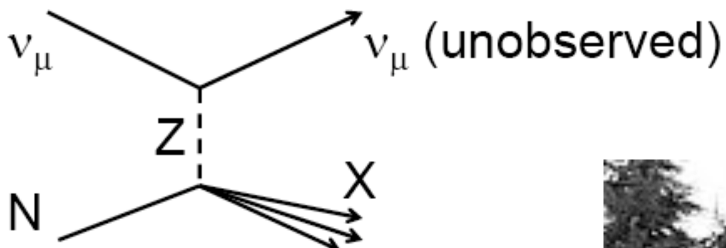
A ν_τ interacted with a nucleon in a steel layer, producing a τ.



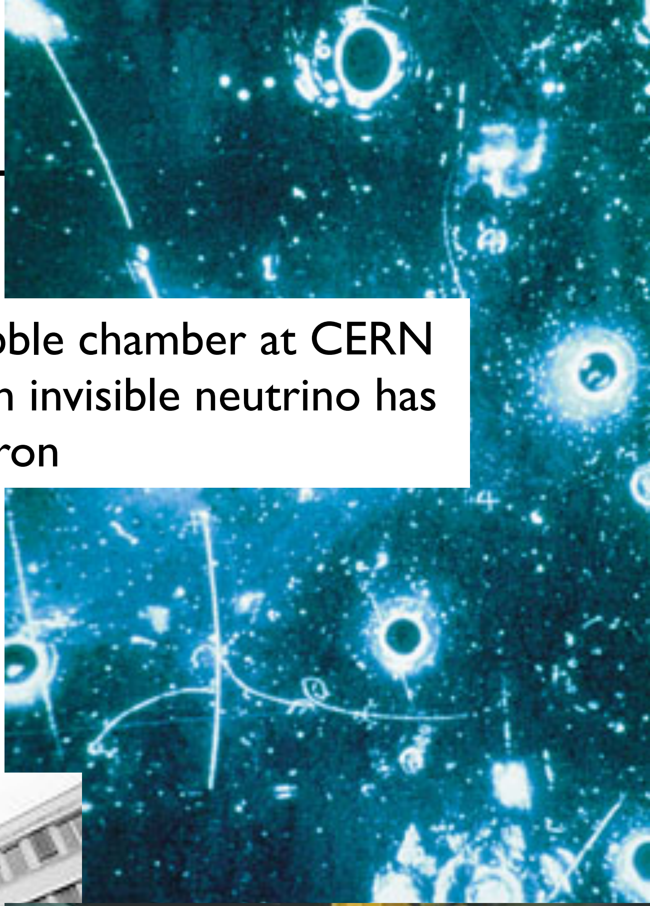
Long tau decay because it decays to one charged particle, the electron, and the decay vertex occurs several sheets downstream from the neutrino interaction vertex.

Neutral Current Discovery (1973)





Major triumph for the Standard Model



Gargamelle bubble chamber at CERN showing how an invisible neutrino has jogged an electron

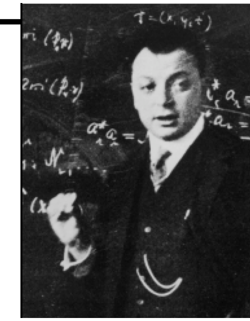
Table 1

	ν-exposure	$\bar{\nu}$-exposure
No. of neutral-current candidates	102	64
No. of charged-current candidates	428	148

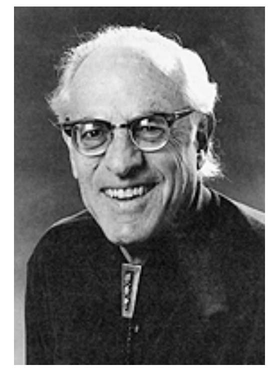
“Standard Model” Neutrino Physics

1914 Electron Spectrum in β decay is continuous

1930 Pauli postulates that a new particle is emitted



1933 Fermi names the new particle neutrino and introduces four-fermion interaction



1956 Reines and Cowan discover the neutrino

1962 At least two neutrinos: $\nu_e \neq \nu_\mu$

1973 Discovery of neutral currents at CERN

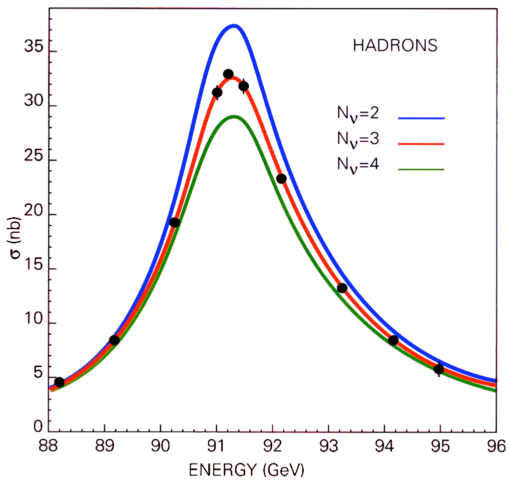
1983 Discovery of the W and Z

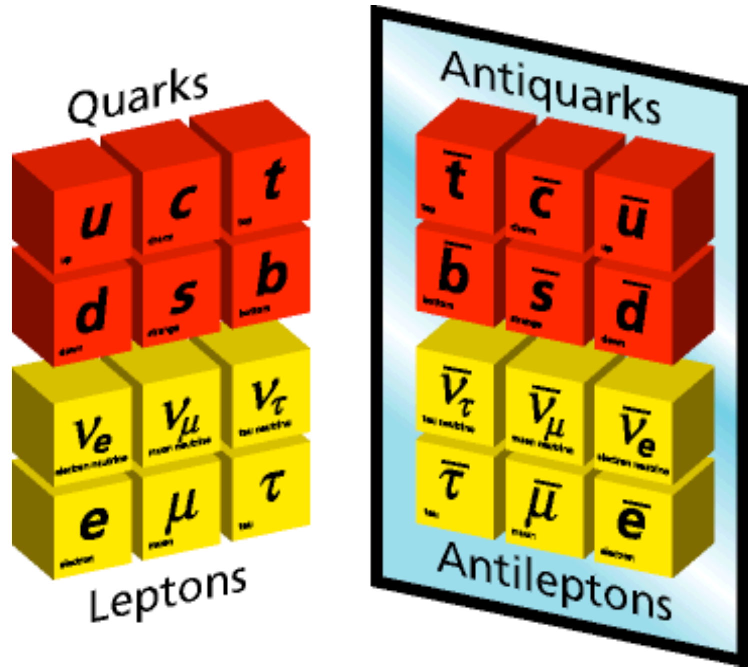
1989 Measurement of Z width at CERN $\rightarrow N_\nu=3$

2002 tau neutrino discovered.

Neutrinos in the Standard Model

Discovery of ν_μ and ν_τ
Accelerator studies of ν

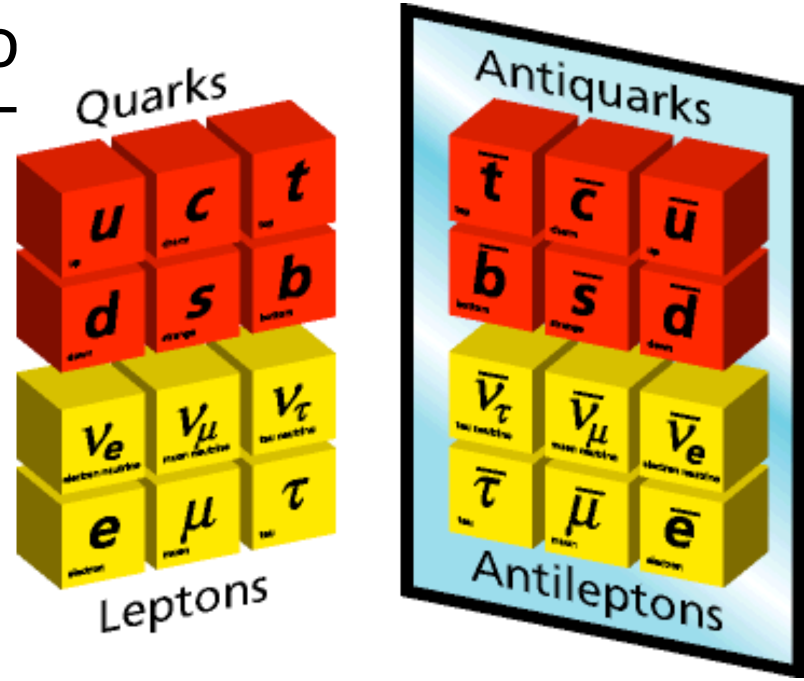




The Standard Model

- 3ν flavors
- upper limits on m_ν from kinematic studies.
- massless ν (*ad hoc* assumption in Standard Model)

Particle Properties of the Neutrino



Interactions weak
(and gravitational) only

Flavors 3 active flavors

Charge

Spin s=1/2

Type

Dirac $\nu \neq \overline{\nu}$
Majorana $\nu = \overline{\nu}$?

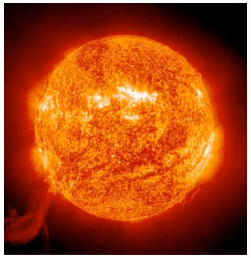
Mass

$m_{\nu e}$ < 2 eV from tritium β decay
$m_{\nu\mu}$ < 170 keV from π decay
$m_{\nu\tau}$ < 18 MeV from τ decay

Birth of Neutrino Astrophysics

1938 Bethe & Critchfield

$p + p \rightarrow {}^2H + e^+ + \nu_e$



1947 Pontecorvo, 1949 Alvarez propose neutrino detection through

${}^{37}Cl + \nu_e \rightarrow {}^{37}Ar + e^-$

1960's Ray Davis builds chlorine detector. John Bahcall, generates first solar model calculations and ν flux predictions.

Light Element Fusion Reactions

$p + p \rightarrow {}^2H + e^+ + \nu_e$ (99.75%)

$p + e^- + p \rightarrow {}^2H + \nu_e$ (0.25%)

${}^2H + p \rightarrow {}^3He + \gamma$

85%: ${}^3He + {}^3He \rightarrow {}^4He + 2p$

~15%: ${}^3He + {}^4He \rightarrow {}^7Be + \gamma$

~10-5%: ${}^3He + p \rightarrow {}^4He + e^+ + \nu_e$

15.07 %: ${}^7Be + e^- \rightarrow {}^7Li + \gamma + \nu_e$

${}^7Li + p \rightarrow \alpha + \alpha$

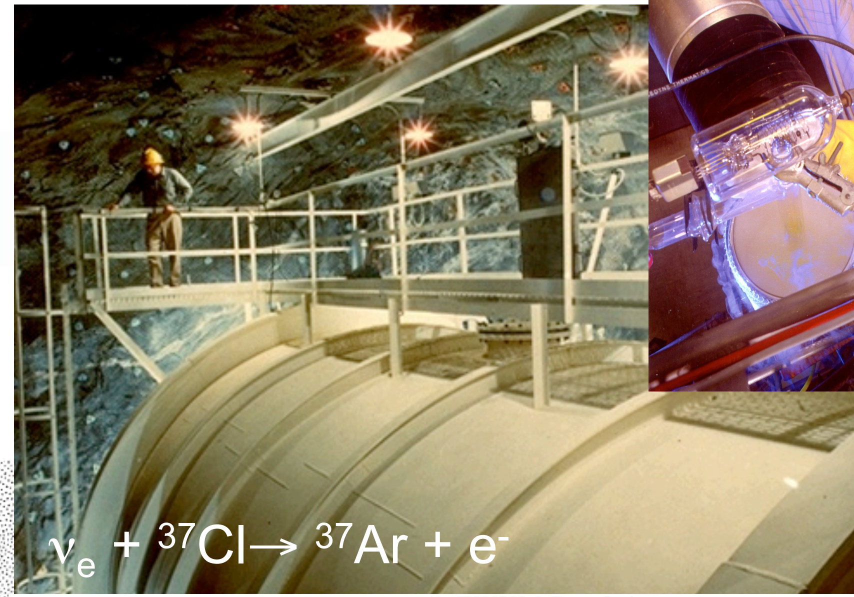
0.02%: ${}^7Be + p \rightarrow {}^8B + \gamma$

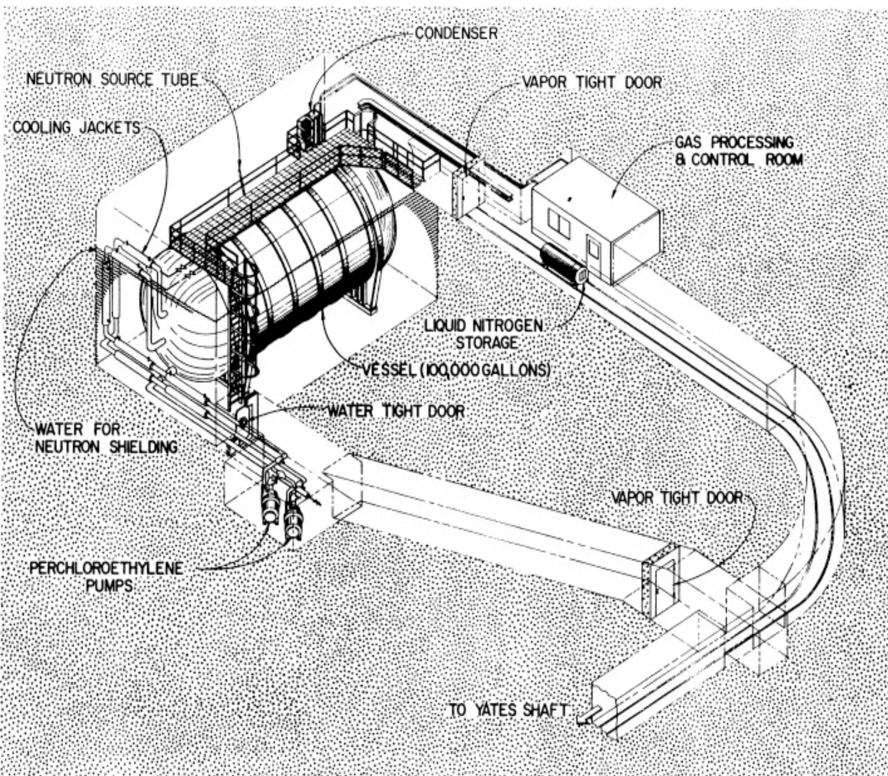
${}^8\mathbf{B} \rightarrow {}^8Be^* + e^+ + \nu_e$

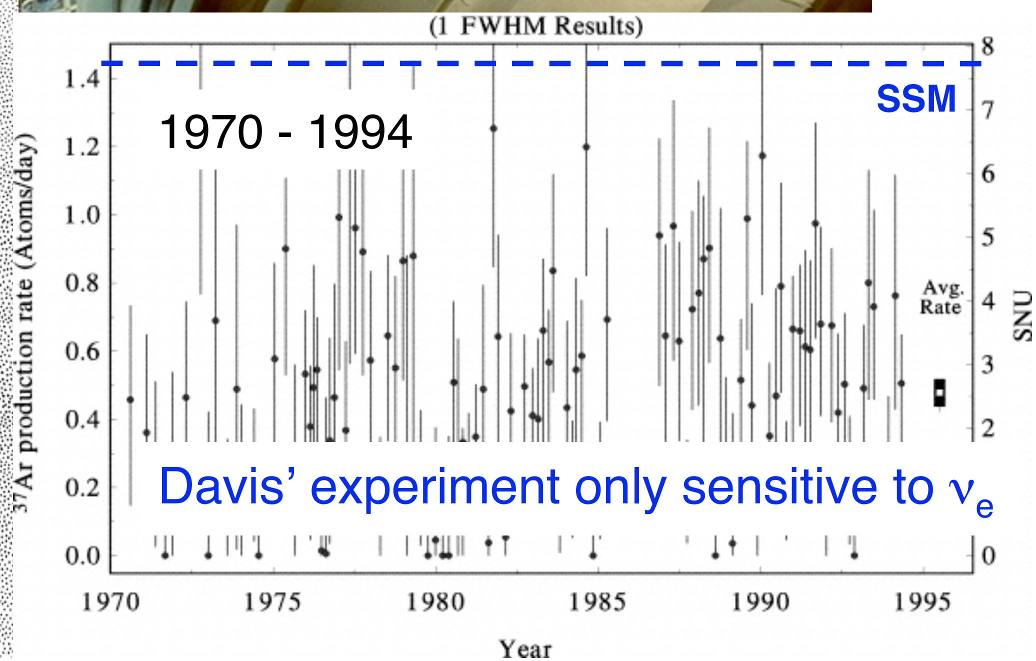
"…to see into the interior of a star and thus verify directly the hypothesis of nuclear energy generation in stars..." (Bahcall, 1964)

Cl-Ar Solar Neutrino Experiment at Homestake

The Nobel Prize in Physics 2002







What is the Solution?

Experimental Errors?

But all experiments show similar effect.

Astrophysics wrong?

Perhaps, but even with all fluxes as free parameters, cannot reproduce the data. $P_{MSM} < 1.7\%$ at 95% CL

KMH, Robertson PRL 77:3270 (1996)

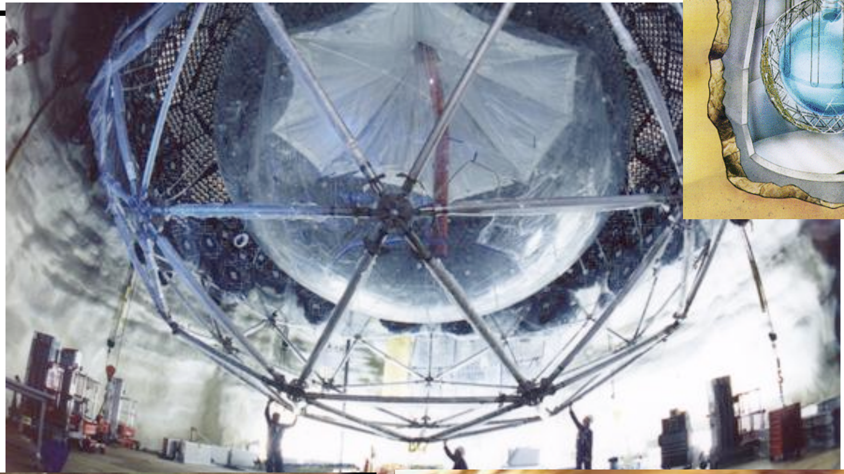
New neutrino physics such as oscillations?

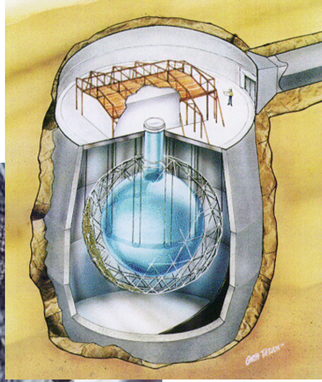
In 1968 Pontecorvo suggests that if lepton number is not conserved, ν_e could change into ν_μ.

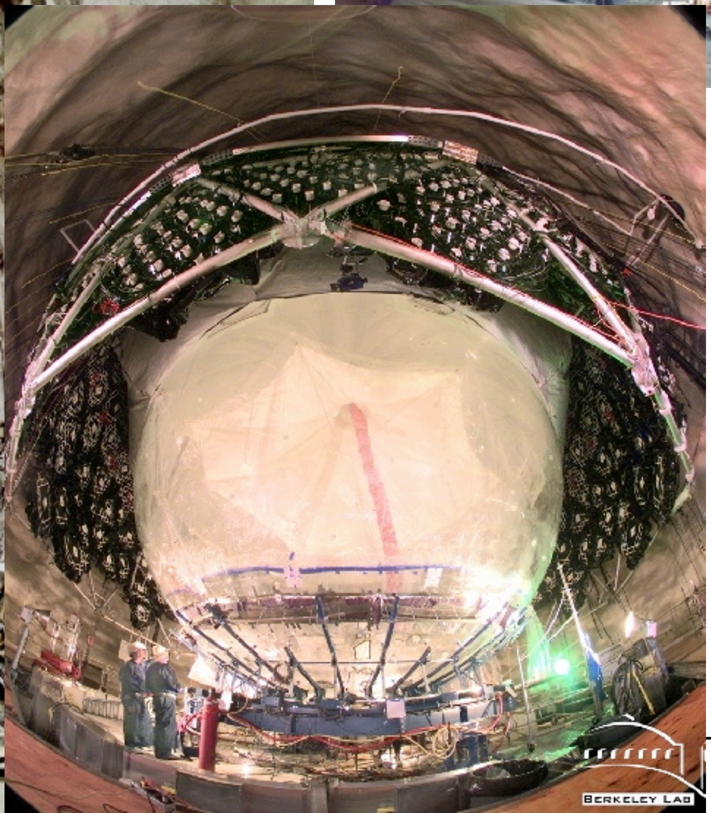
Since the Cl-Ar detector was sensitive only to ν_e, it would appear that the flux was low.

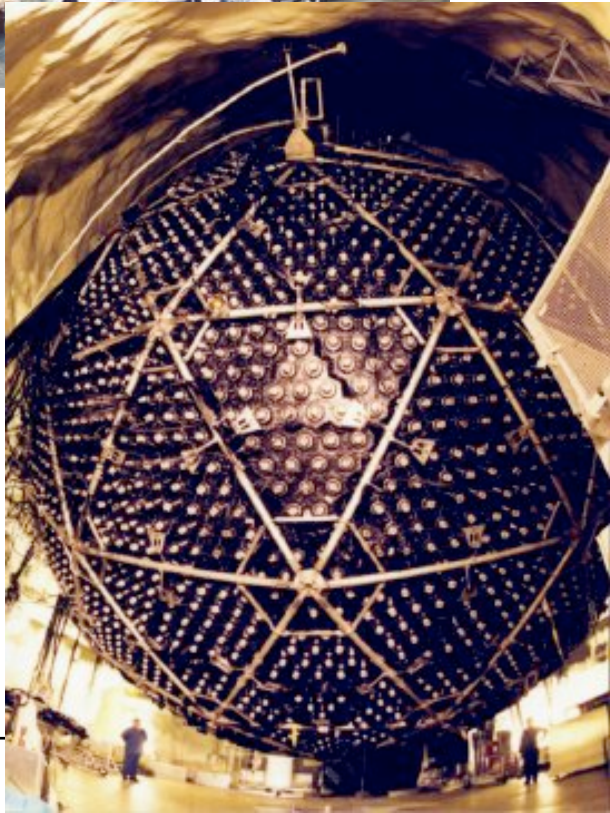
Бруно Понтекорво

The Sudbury Neutrino Observatory

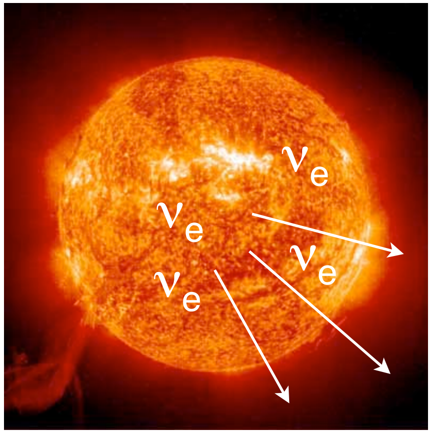








The Solar Neutrino Problem and Its Resolution



Too few ν_e observed from the Sun.

Even with all solar neutrino fluxes as free parameters, cannot reproduce the data. $P_{MSM} < 1.7\%$ at 95% CL

KMH, Robertson PRL 77:3270 (1996)

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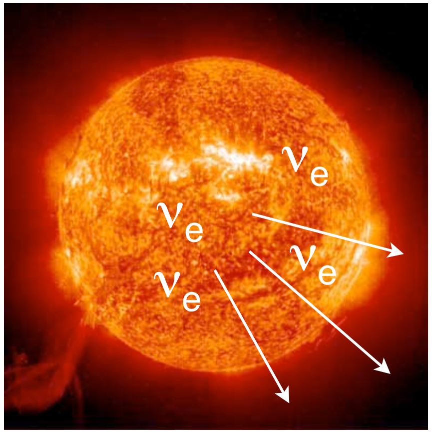

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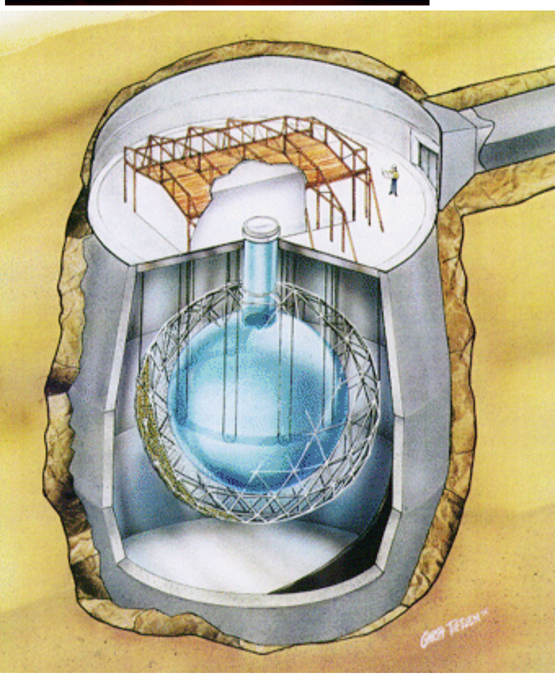
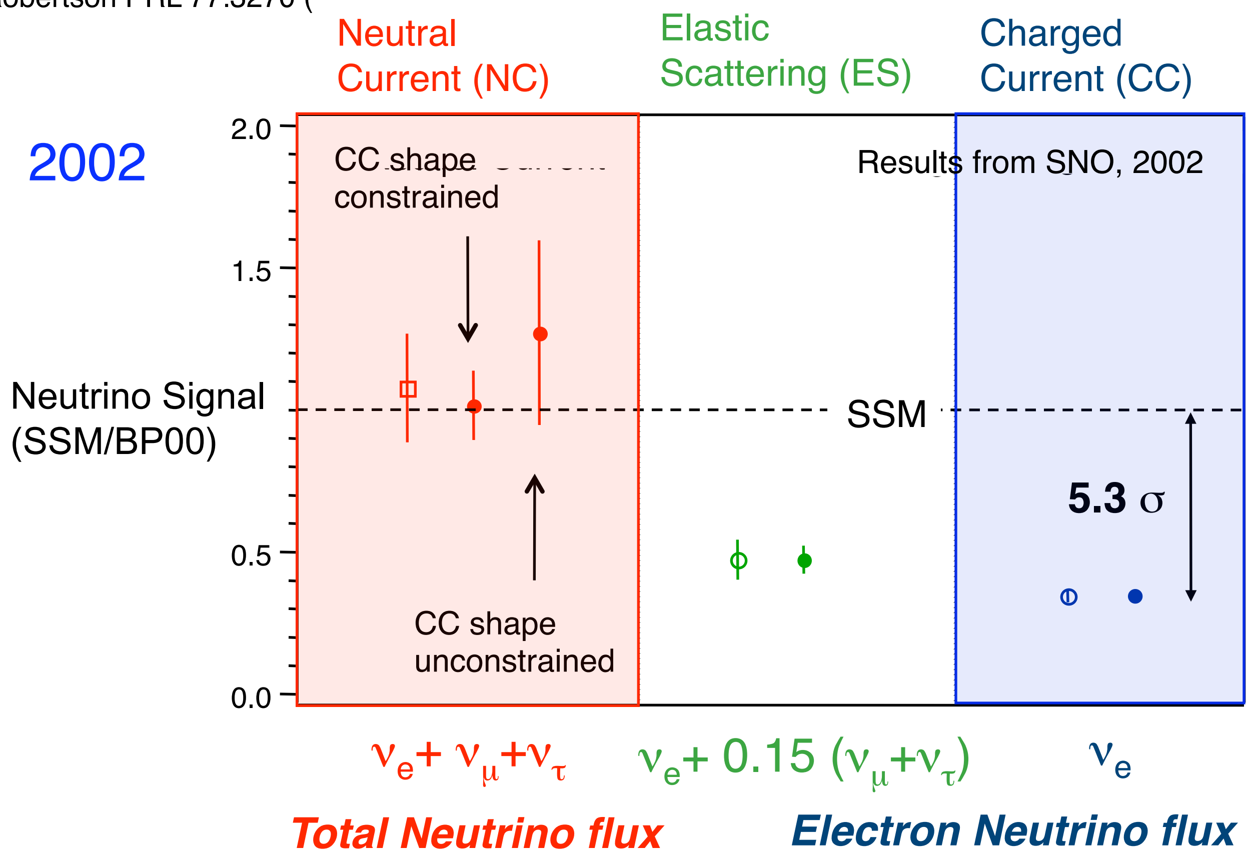


2002



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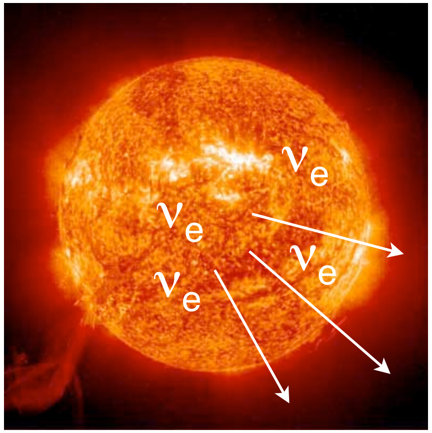

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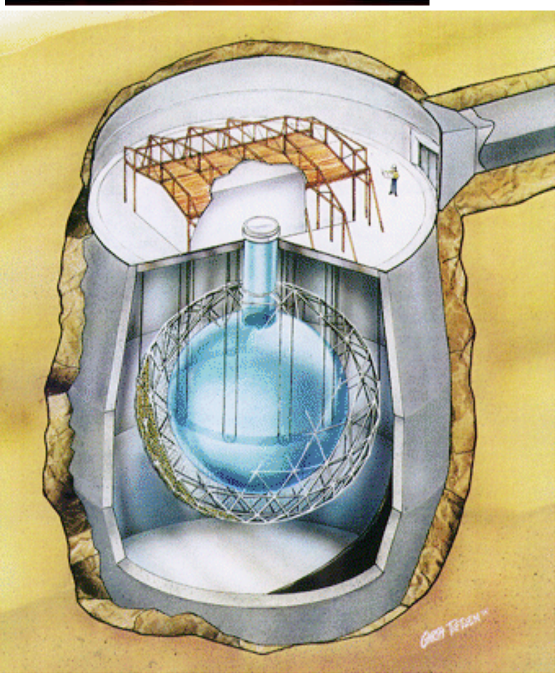
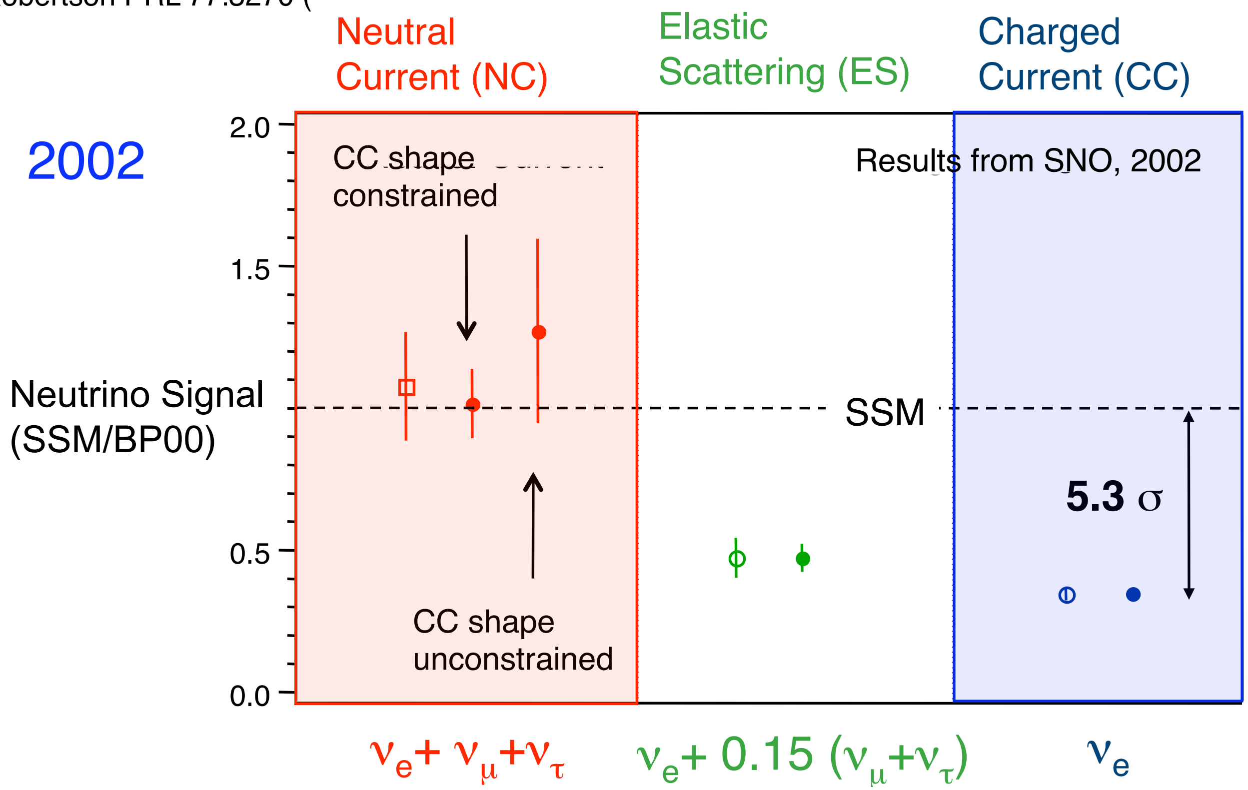
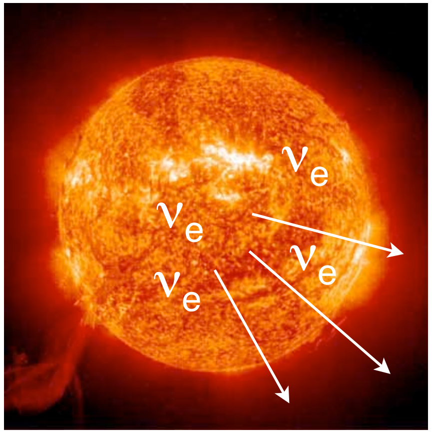




2/3 of initial solar ν_e are observed at SNO to be $\nu_{\mu,\tau}$

The Solar Neutrino Problem and Its Resolution



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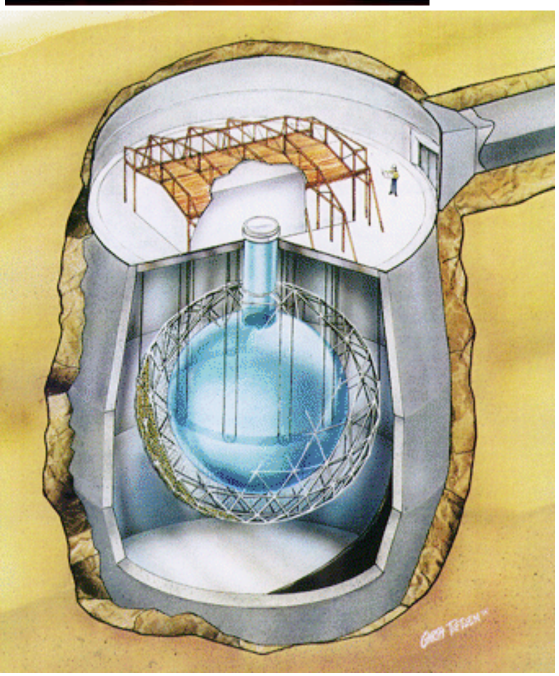
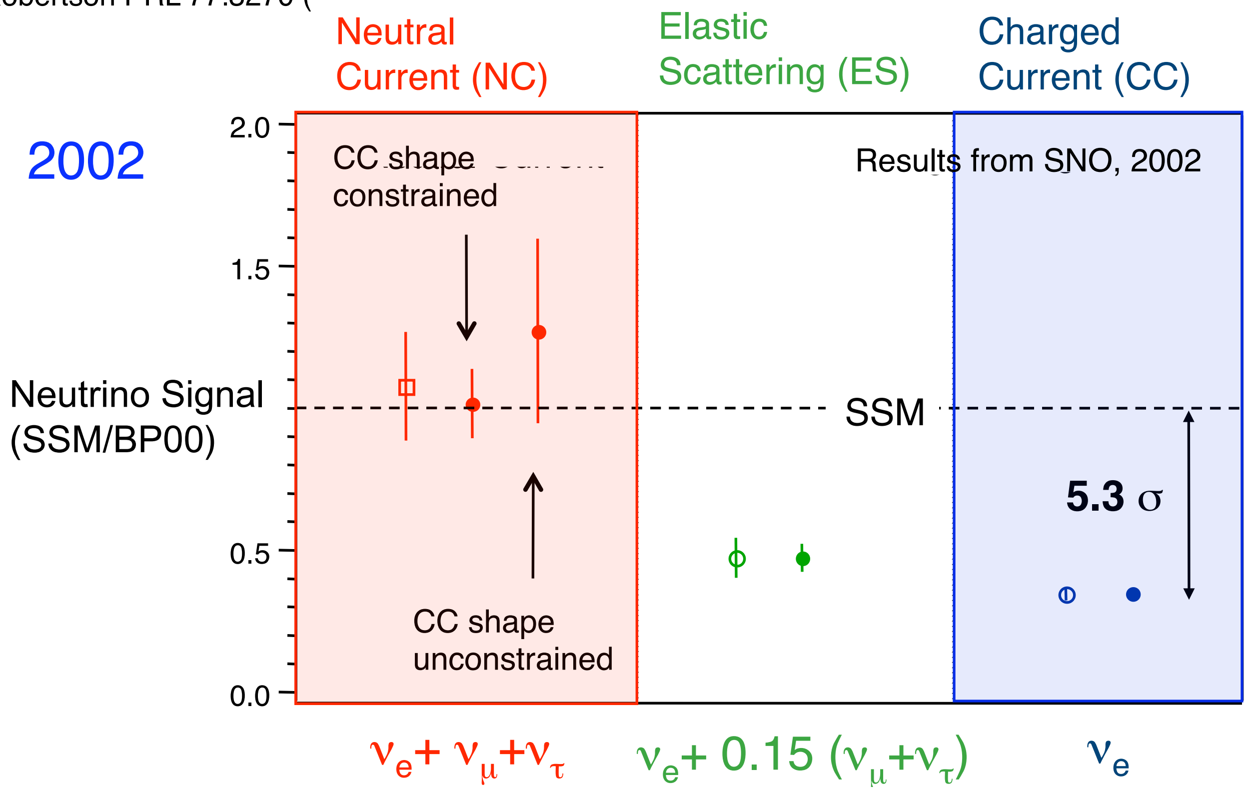
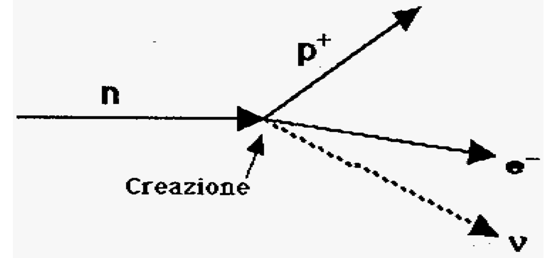




2/3 of initial solar ν_e are observed at SNO to be $\nu_{\mu,\tau}$

Model-independent evidence for solar neutrino flavor change

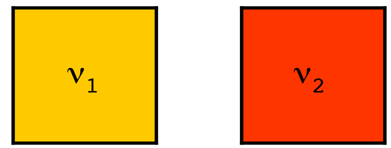
Neutrino Oscillation



Neutrino States

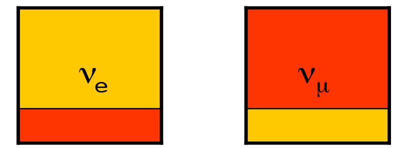
Mass States

First Second



Weak States

First Second



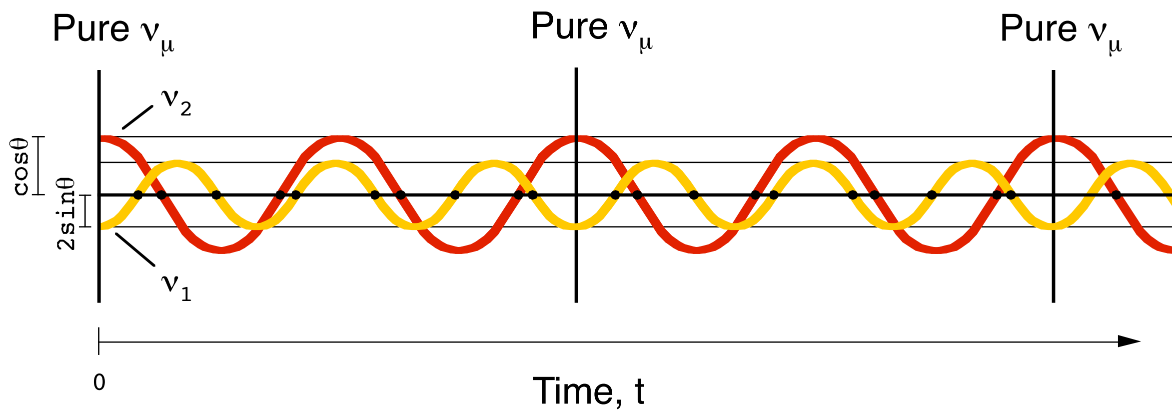
$$
\begin{aligned}
|\nu_a\rangle &= \cos\theta|\nu_1\rangle - \sin\theta|\nu_2\rangle \\
|\nu_b\rangle &= \sin\theta|\nu_1\rangle + \cos\theta|\nu_2\rangle
\end{aligned}
$$

$$
\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{bmatrix} \cos\theta & \sin\theta \\ 2\sin\theta & \cos\theta \end{bmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}
$$

Time Evolution

Бруно Понтекорво

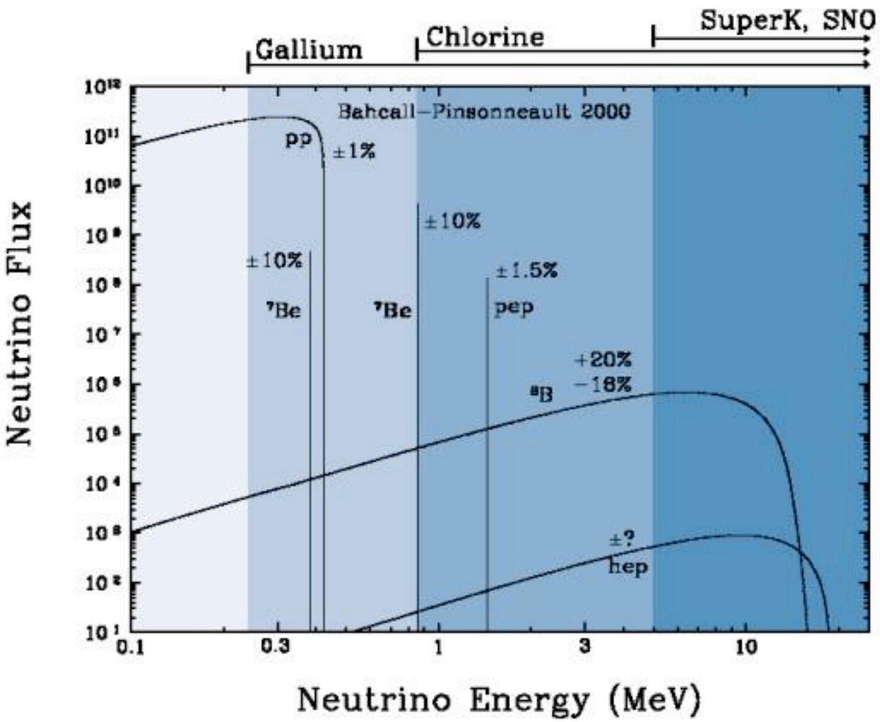
Pontecorvo, 1968

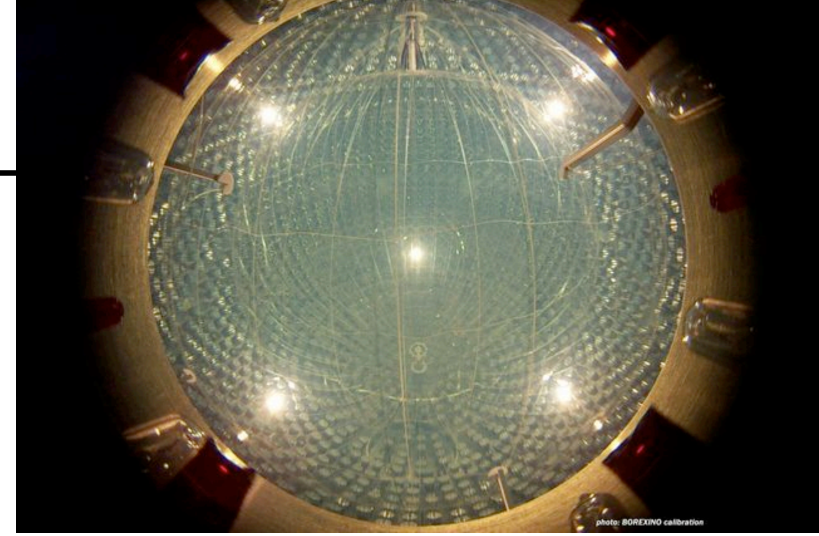


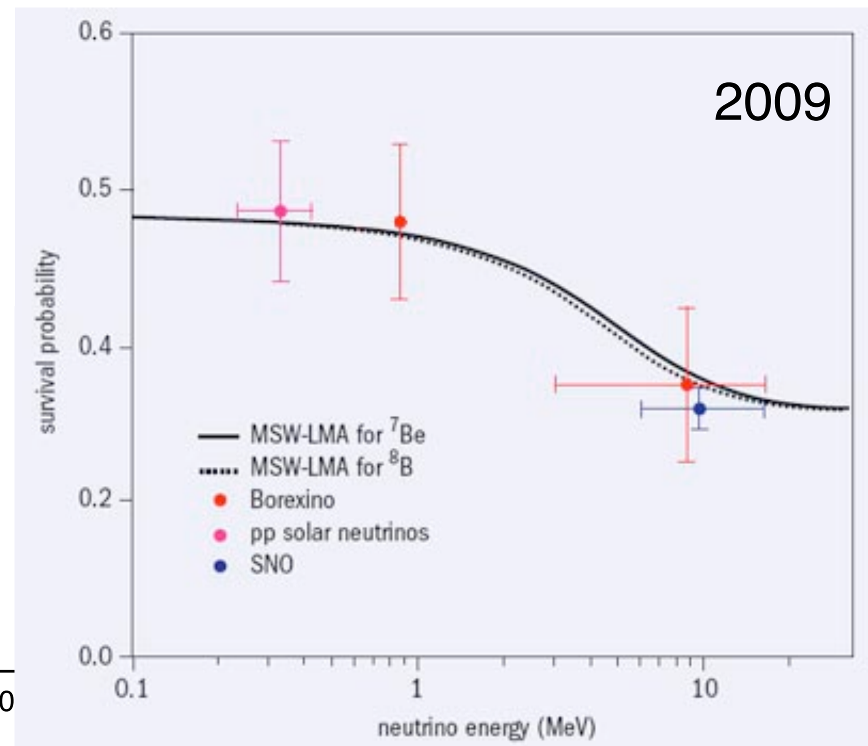
$$
P_{i\to i} = \sin^2 2\theta \sin^2\left(1.27\Delta m^2 \frac{L}{E}\right)
$$

oscillation → energy and baseline- dependent effect

Borexino







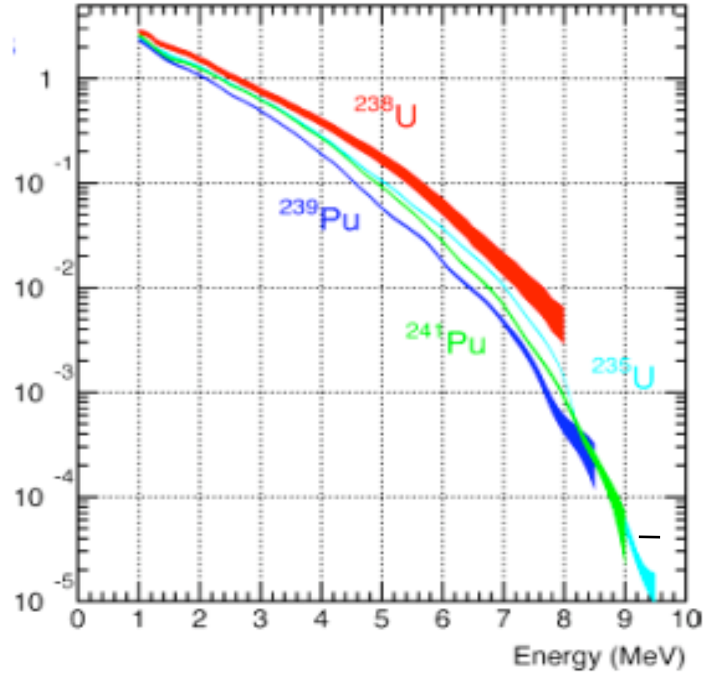
vacuum-matter transition in solar neutrino oscillation

Reactor Antineutrinos in Japan

Japanese Reactors

55 reactors

Reactor Antineutrinos



^{235}U:^{238}U:^{239}Pu:^{241}Pu = 0.570: 0.078: 0.0295: 0.057

~ 200 MeV per fission

~ 6 $\bar{\nu}_e$ per fission

~ 2 x 10^{20} $\bar{\nu}_e/GW_{th}$-sec

reactor $\bar{\nu}$ flux ~ 6 x $10^6/cm^2/sec$

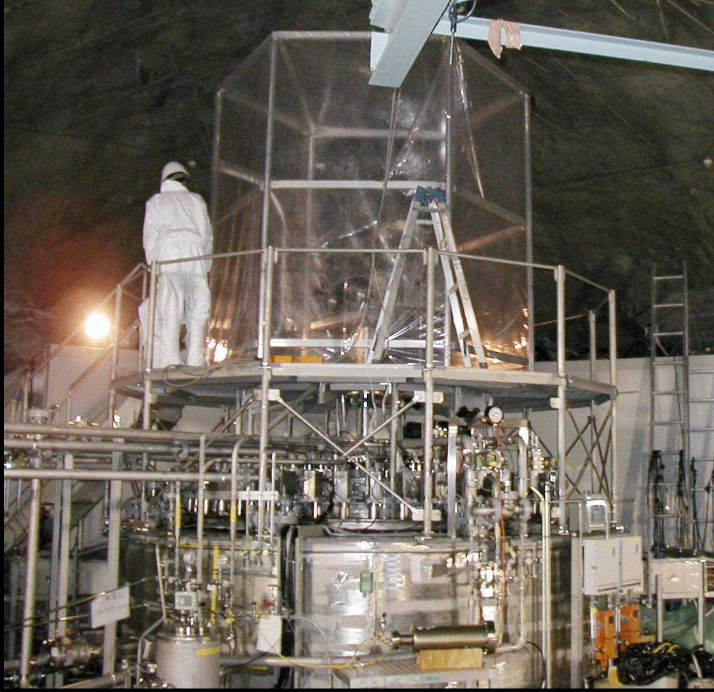
KamLAND Antineutrino Detector

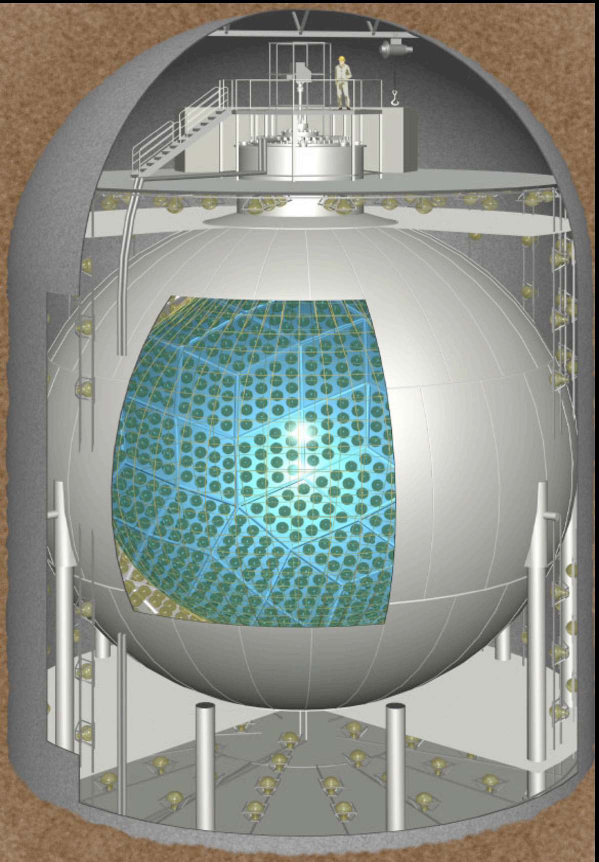
$\overline{\nu}_e + p \rightarrow e^+ + n$

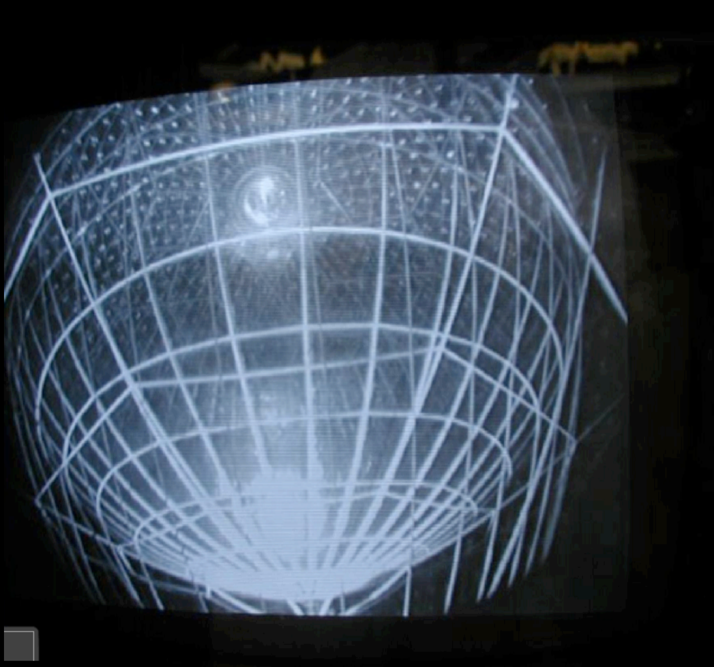
through inverse β-decay

$$E_{\overline{\nu}_e} \simeq E_p + \overline{E}_n + 0.8\,\mathrm{MeV},$$

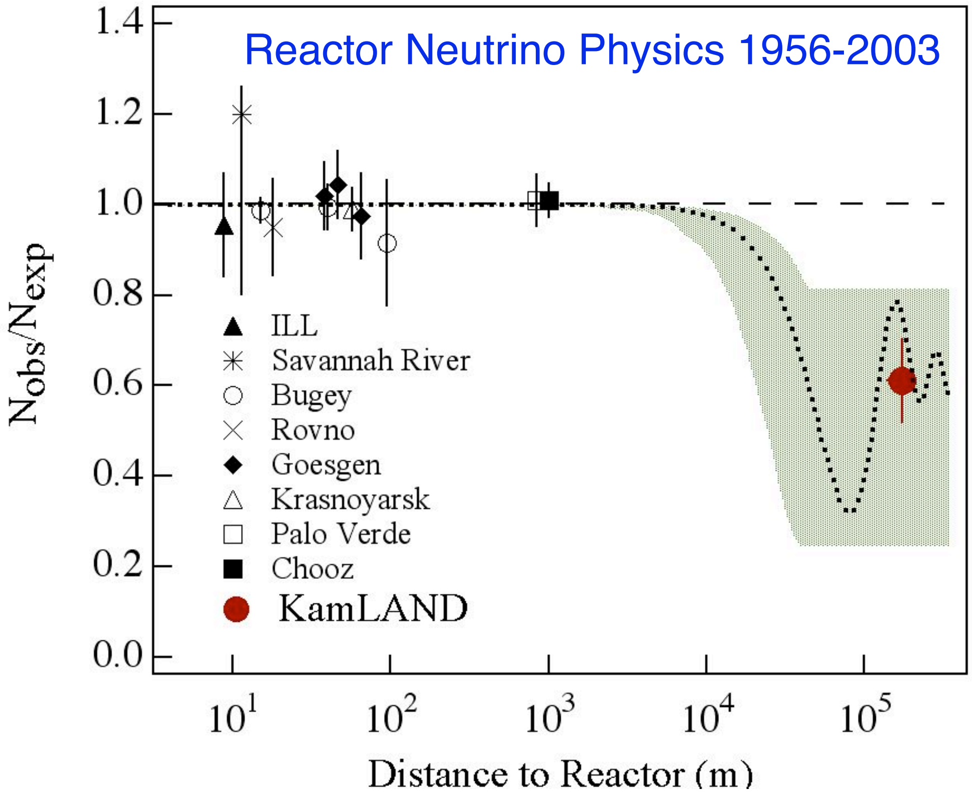
liquid scintillator target:
- proton rich > 10^{31} protons
- good light yield







KamLAND 2003:
First Direct Evidence for Reactor $\overline{\nu}_e$ Disappearance

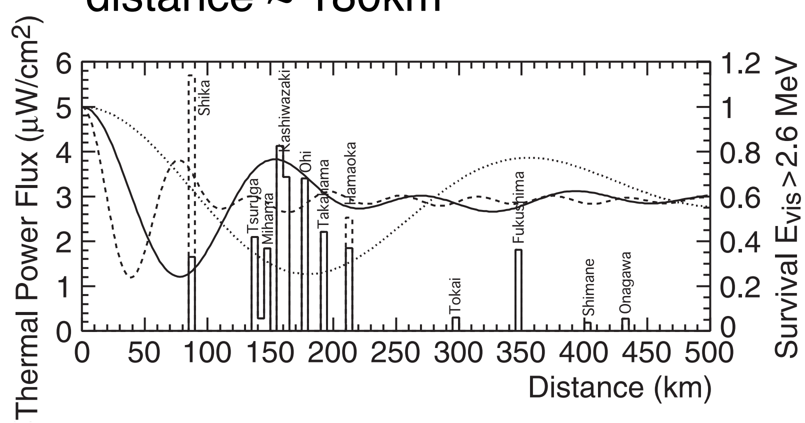


PRL 90:021802 (2003)

Observed $\overline{\nu}_e$	54 events
No-Oscillation	86.8 ± 5.6 events
Background	1 ± 1 events
Livetime:	162.1 ton-yr

Japan

mean, flux-weighted reactor distance ~ 180km



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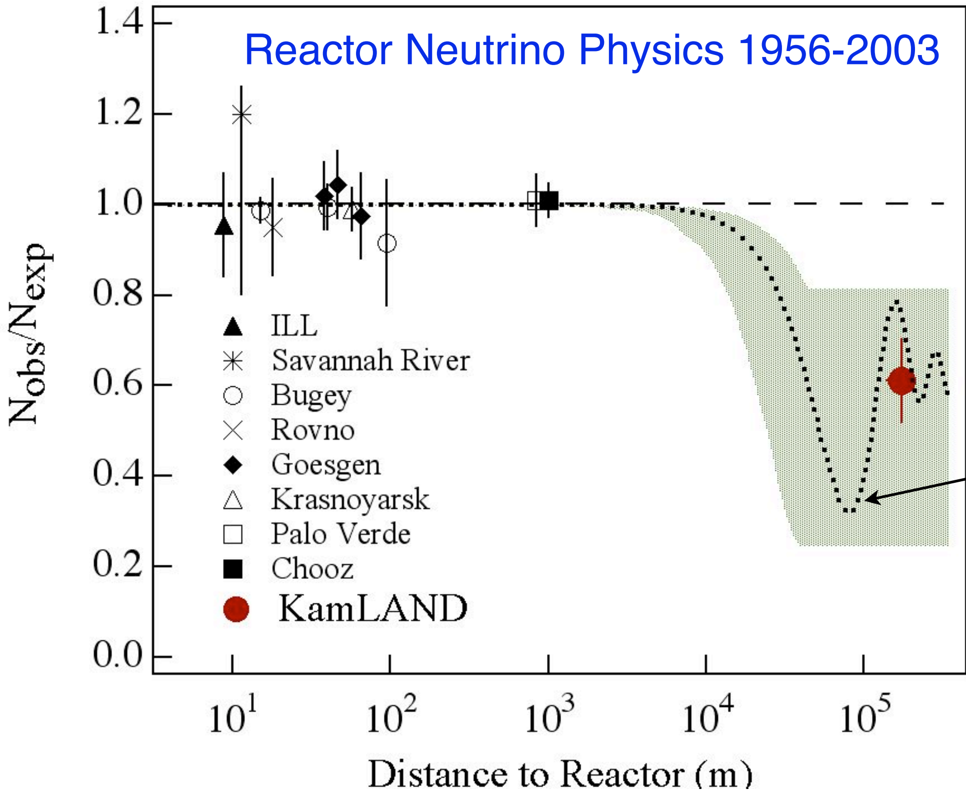

suggested by solar neutrino experiments

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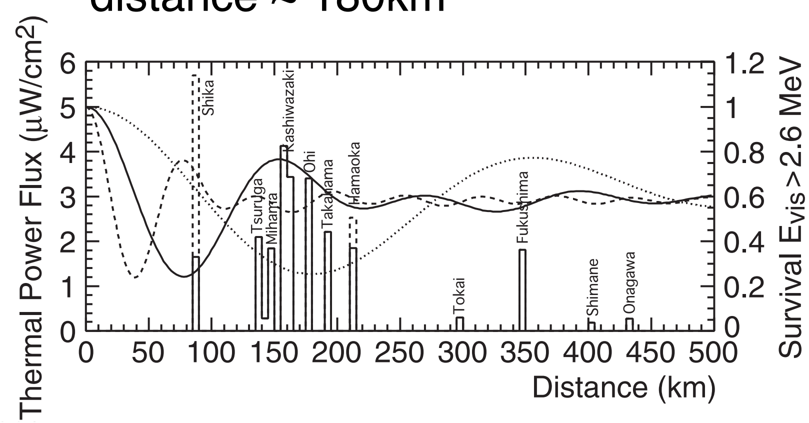

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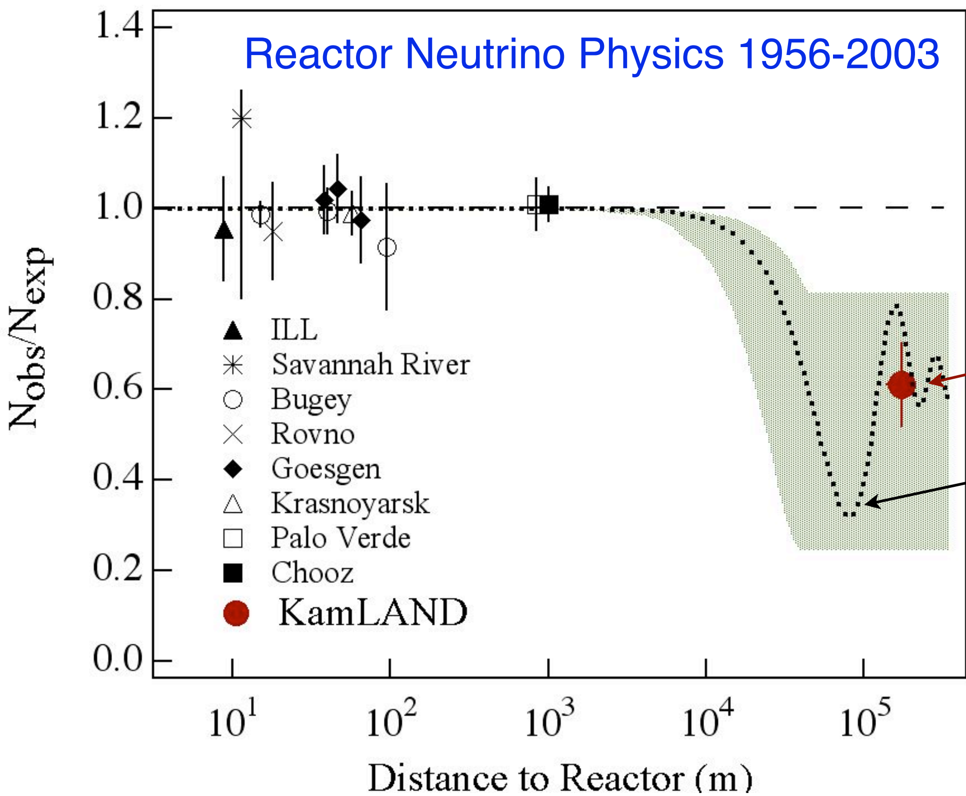

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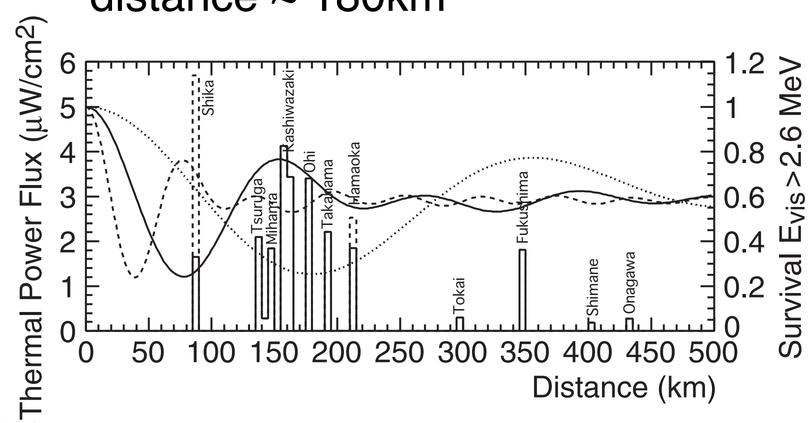
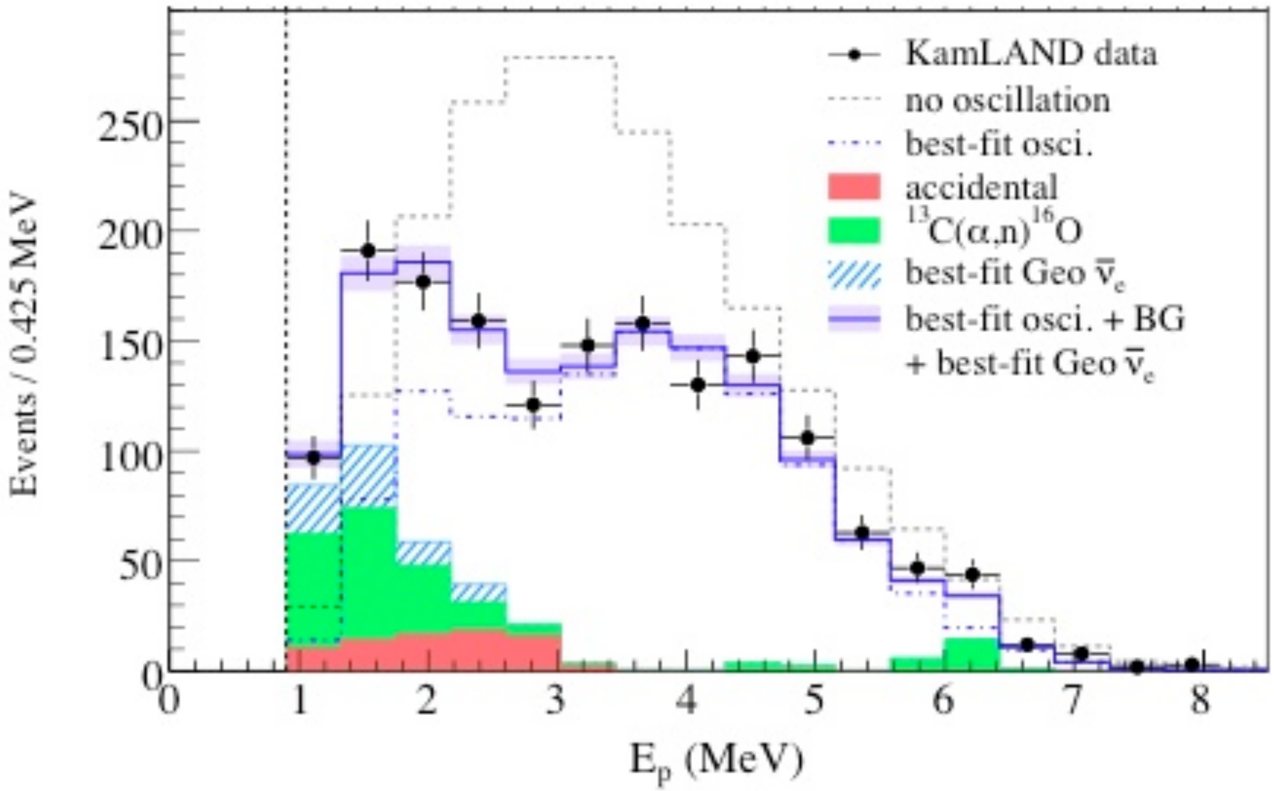


KamLAND 2008: Precision Measurement of Oscillation

Prompt event energy spectrum for $\overline{\nu_e}$



number of events

expected: 2179 ± 89 (syst)

observed: 1609

bkgd: 276 ± 23.5

Spectral Distortions: A unique signature of neutrino oscillation!

significance of distortion: > 5σ

best-fit χ^2/ndf=21/16 (18% C.L.)

significance of disappearance

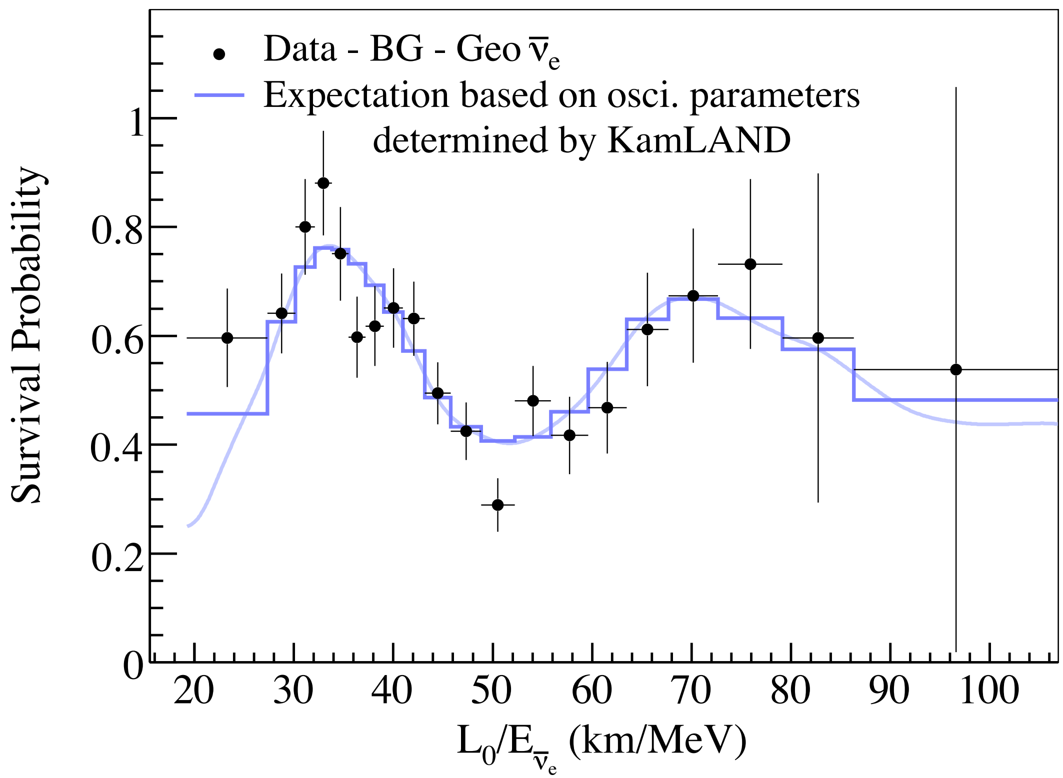
(with 2.6 MeV threshold): 8.5σ

no-osc χ^2/ndf=63.9/17

KamLAND 2008: Precision Measurement of Oscillation

L/E Dependence

oscillation $P_{ee} = 1 - \sin^2 2\theta \sin^2(\frac{\Delta m^2}{4}\frac{L}{E})$



Solar neutrino problem solved! L/E figure demonstrates $\bar{\nu}$ oscillation.

1970-1995 first identified by Ray Davis (missing solar ν_e)
2002-2008 SNO observes neutrino flavor change, finds evidence for neutrino mass
2003-2008 KamLAND demonstrates $\bar{\nu}$ oscillation, precision measurement of Δm^2

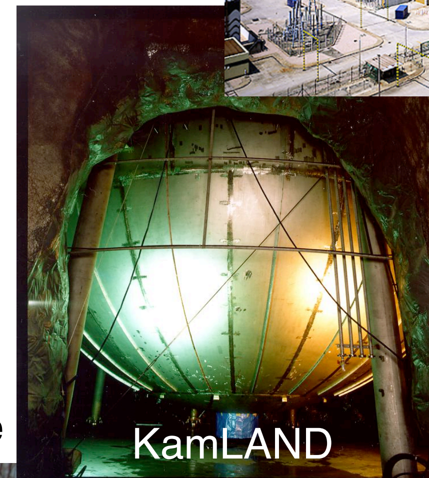
Neutrino Physics at Reactors

Next - Discovery and precision measurement of θ_{13}

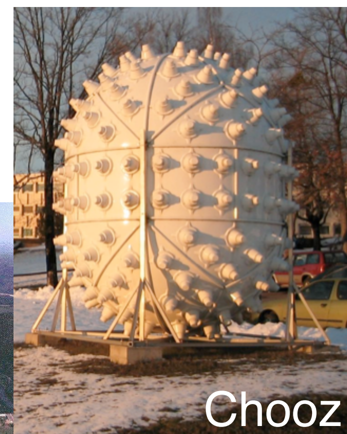
2008 - Precision measurement of Δm_{12}^2 . Evidence for oscillation

2004 - Evidence for spectral distortion

2003 - First observation of reactor antineutrino disappearance



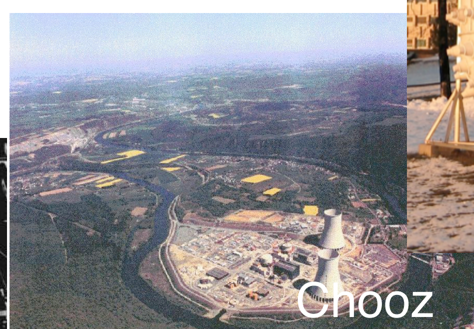
1995 - Nobel Prize to Fred Reines at UC Irvine



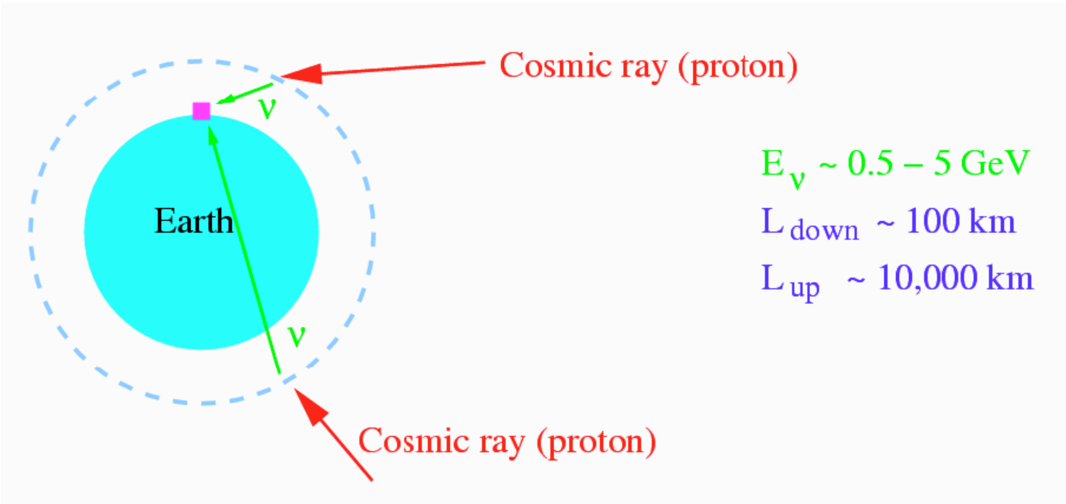
1980s & 1990s - Reactor neutrino flux measurements in U.S. and Europe

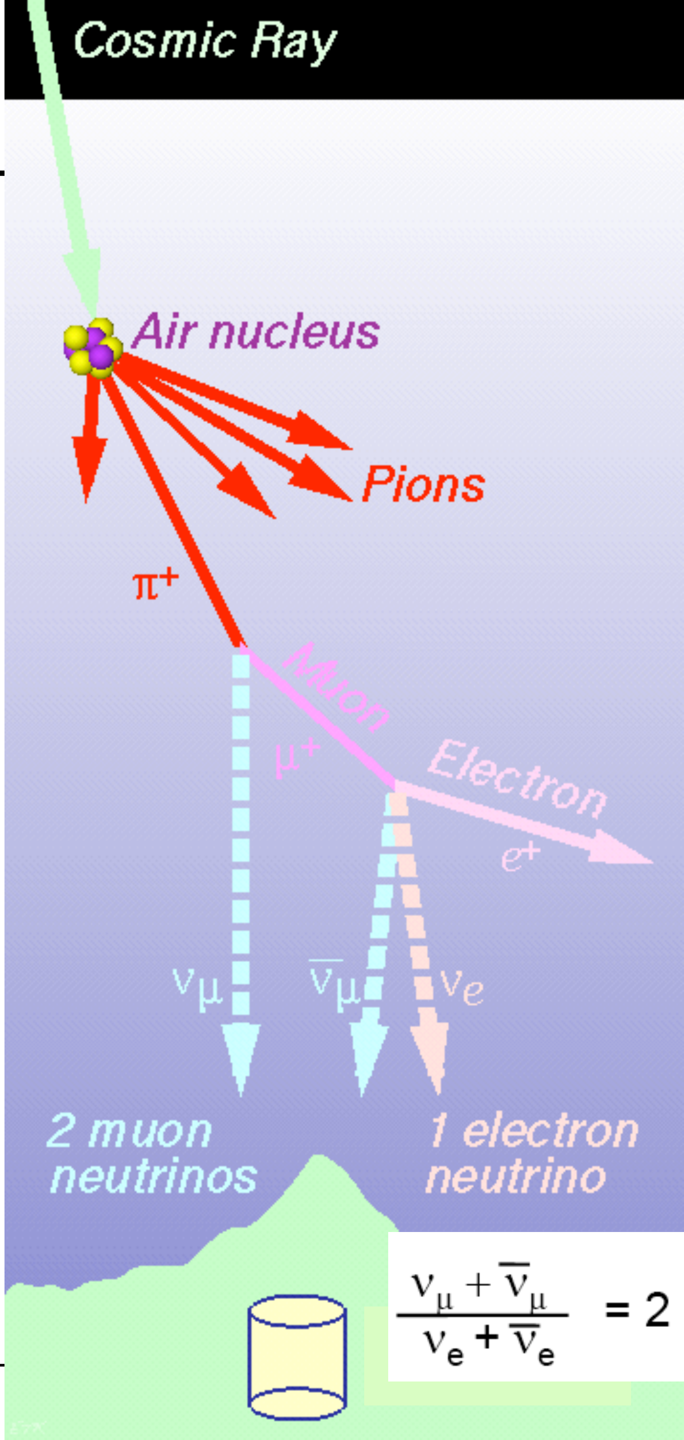
Past Reactor Experiments
Hanford
Savannah River
ILL, France
Bugey, France
Rovno, Russia
Goesgen, Switzerland
Krasnoyark, Russia
Palo Verde
Chooz, France

1956 - First observation of (anti)neutrinos

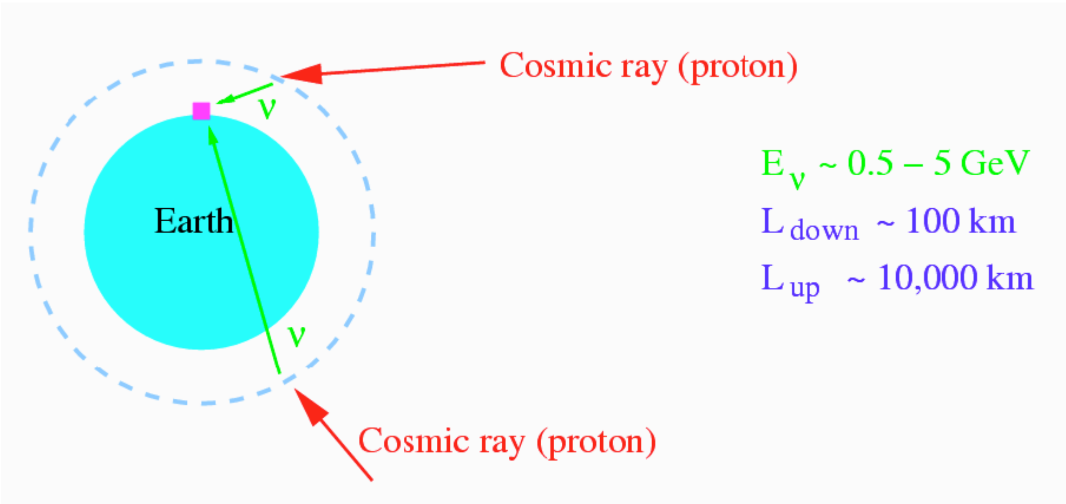


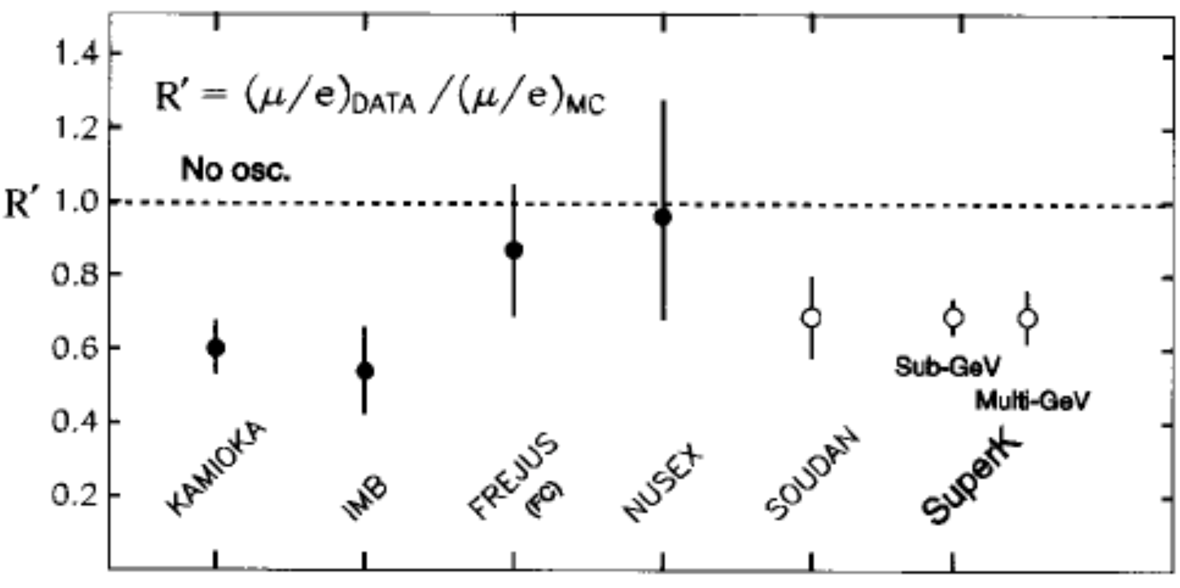
Atmospheric Neutrino Studies

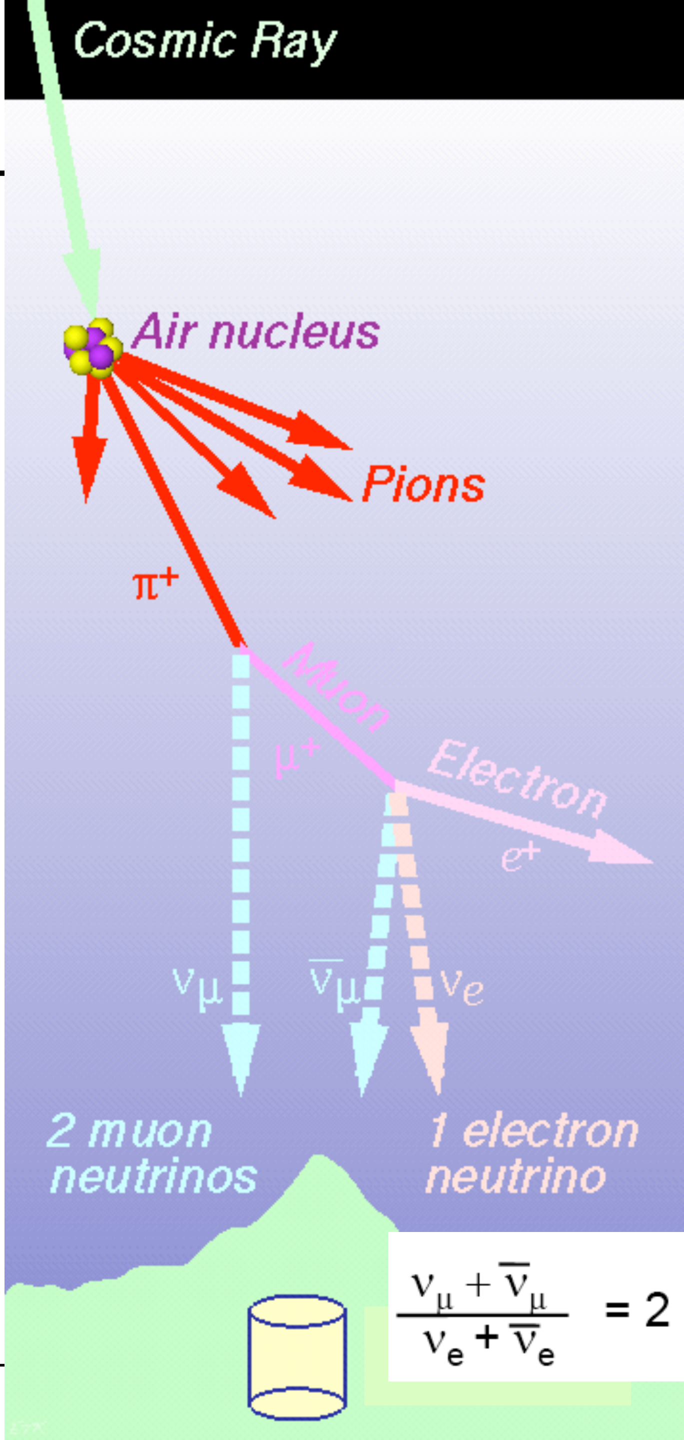




Atmospheric Neutrino Studies

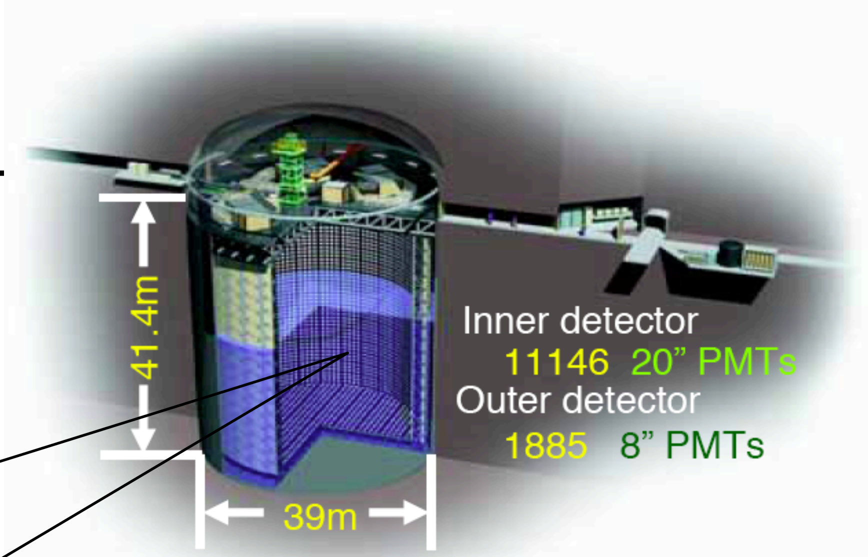


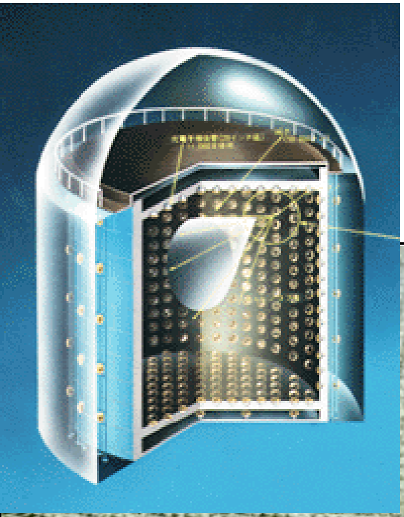


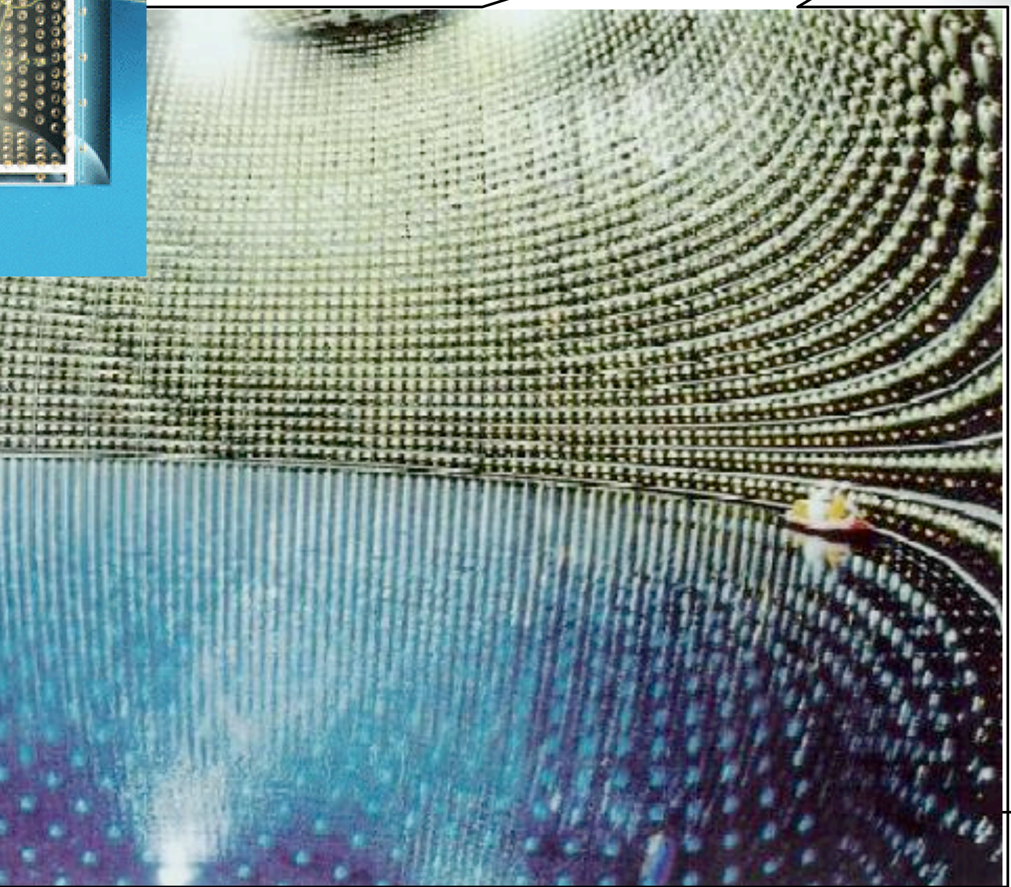


Super-Kamiokande

Atmospheric Neutrino Studies

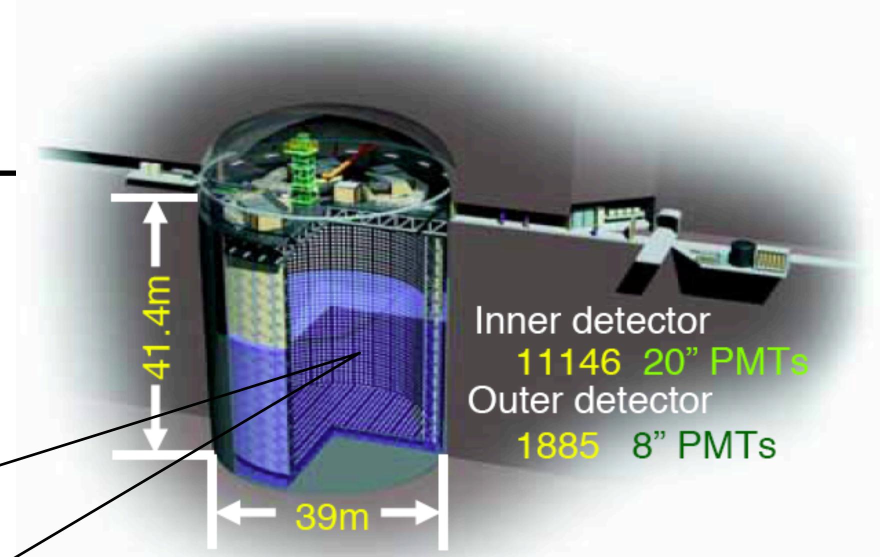


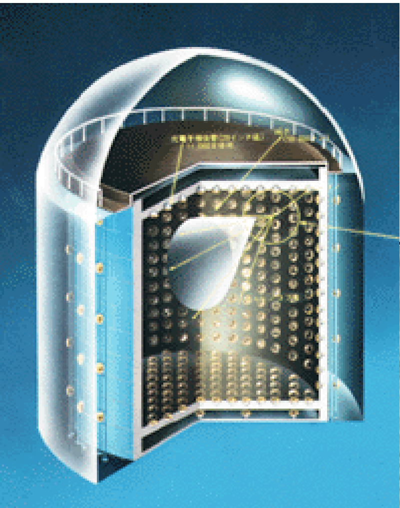


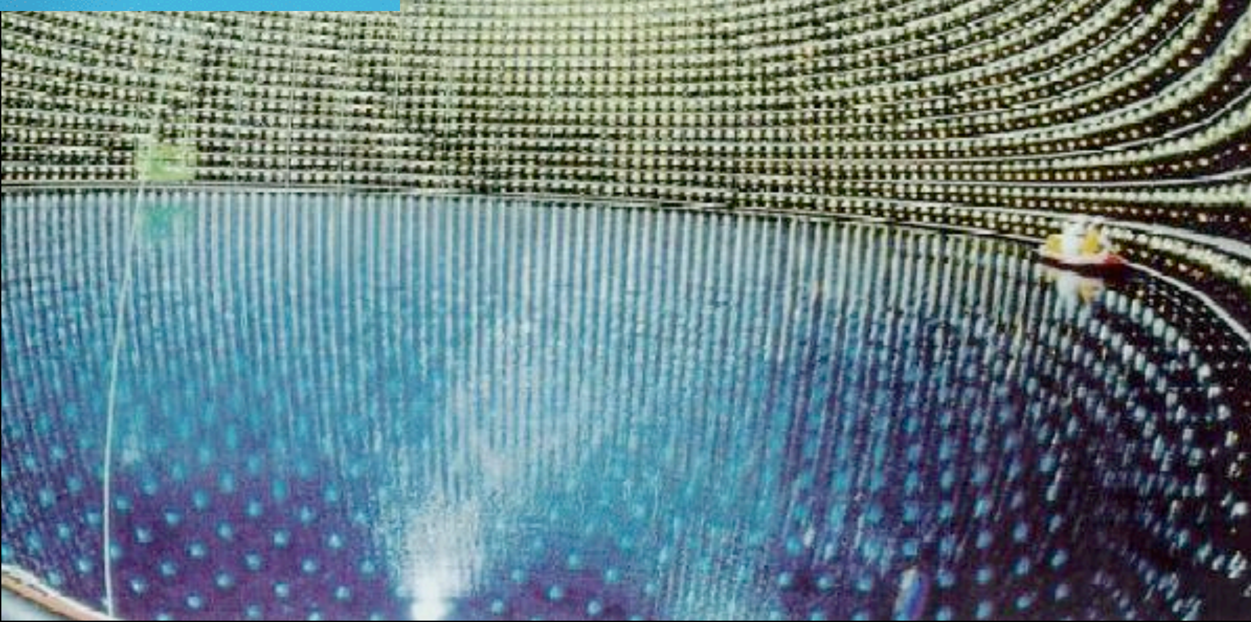


Super-Kamiokande

Atmospheric Neutrino Studies

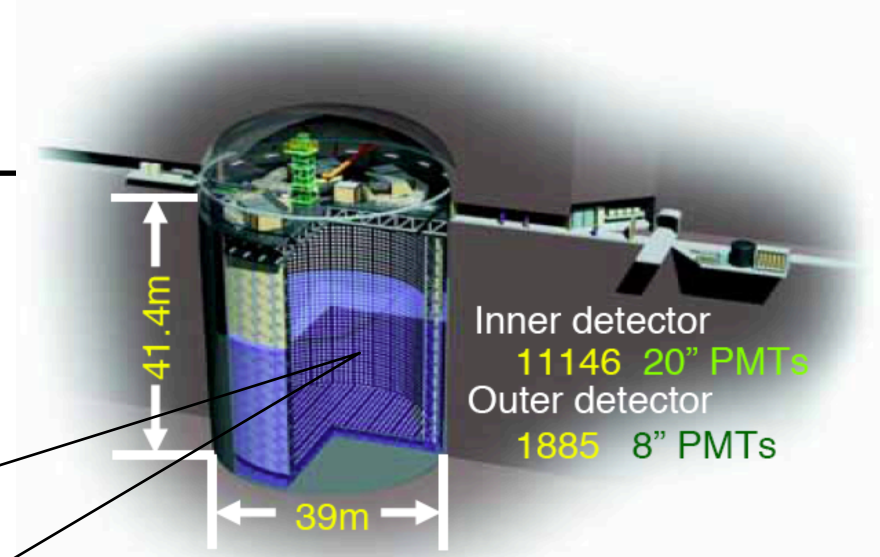


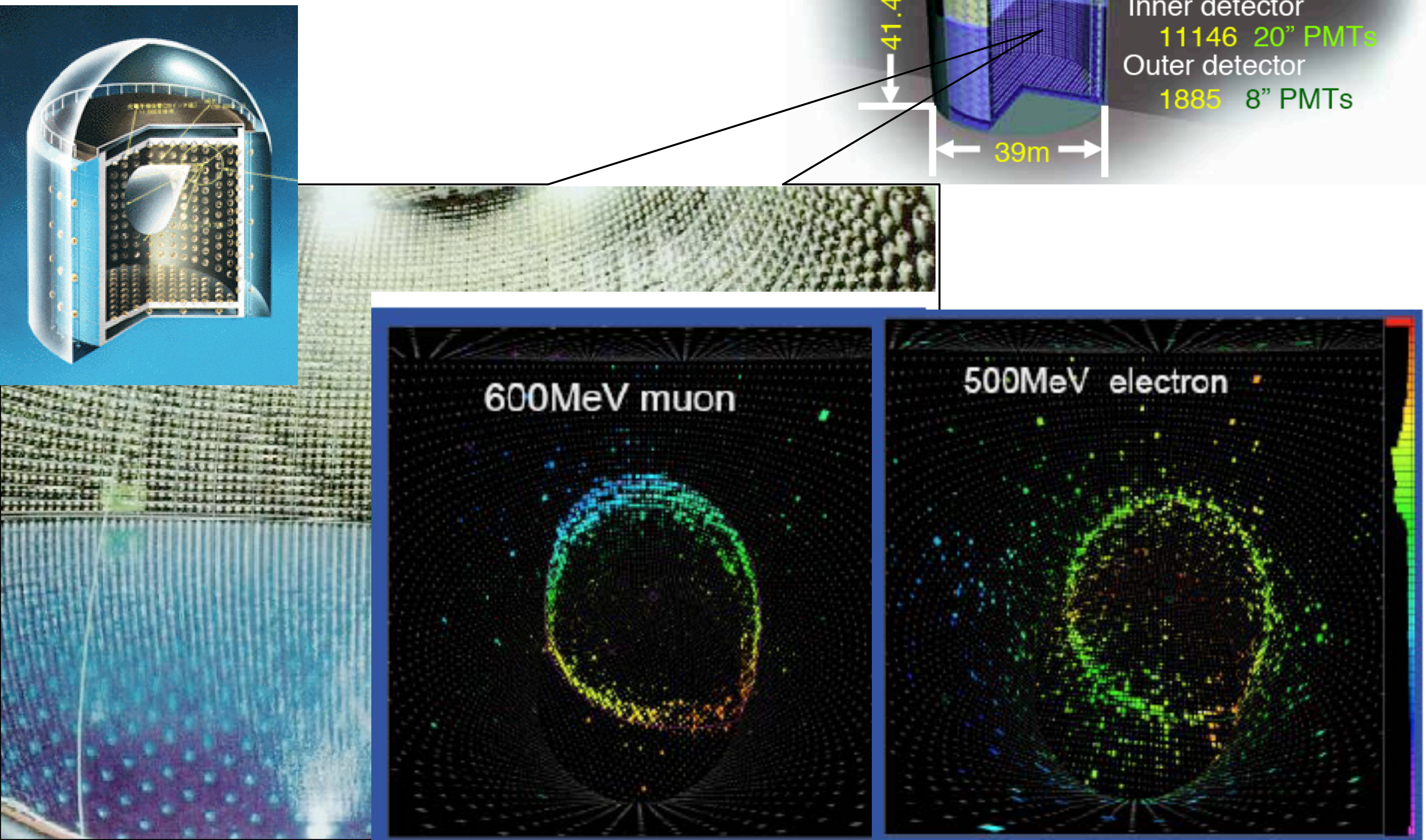




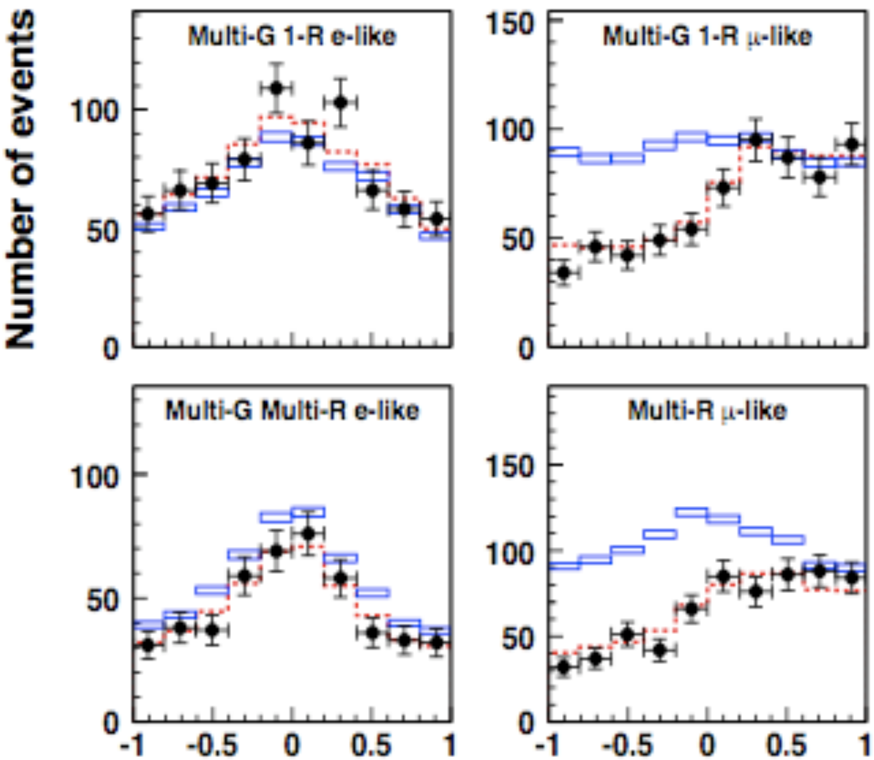
Super-Kamiokande

Atmospheric Neutrino Studies

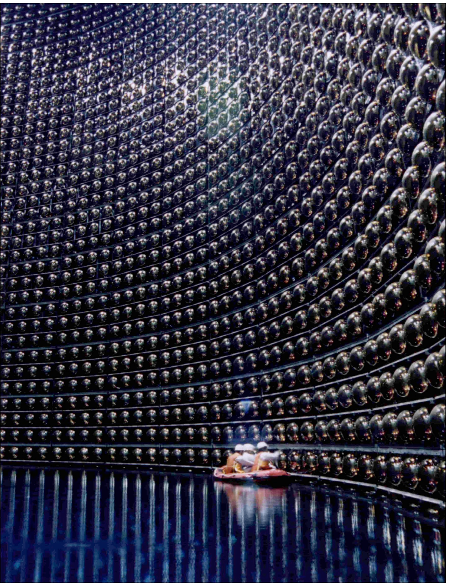




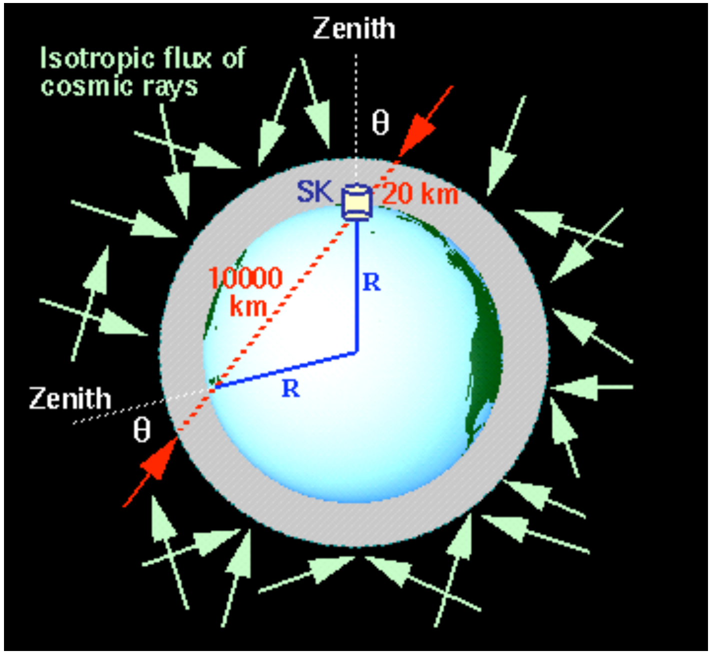
Atmospheric Neutrino Flavor Change



1998



Super-K



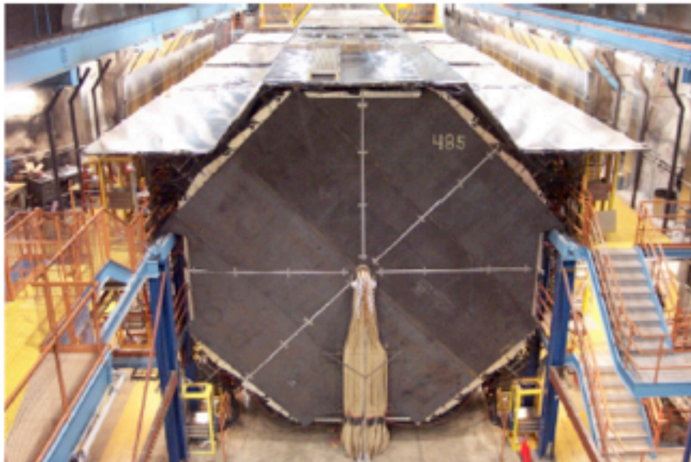
evidence for ν_μ disappearance: zenith-angle dependence

$\Delta m^2 = 2.5 \times 10^{-3}\,\mathrm{eV}^2 \neq 0 \rightarrow$ at least 1 $m_\nu \neq 0$

Mixing angle is quite large ($\theta \sim 45°$)

Precision Science with Accelerator ν

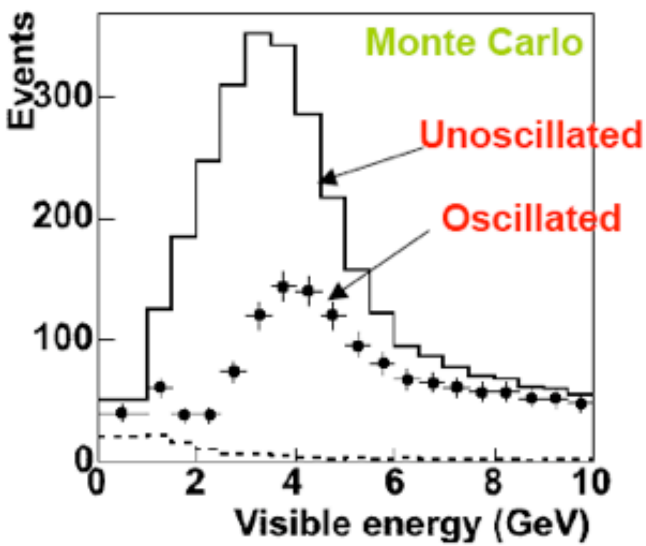
Minos



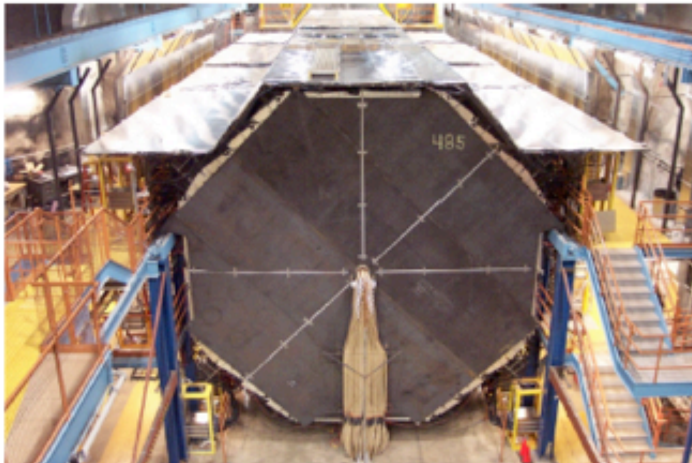
5.4 kton MINOS far detector

1 kton near detector

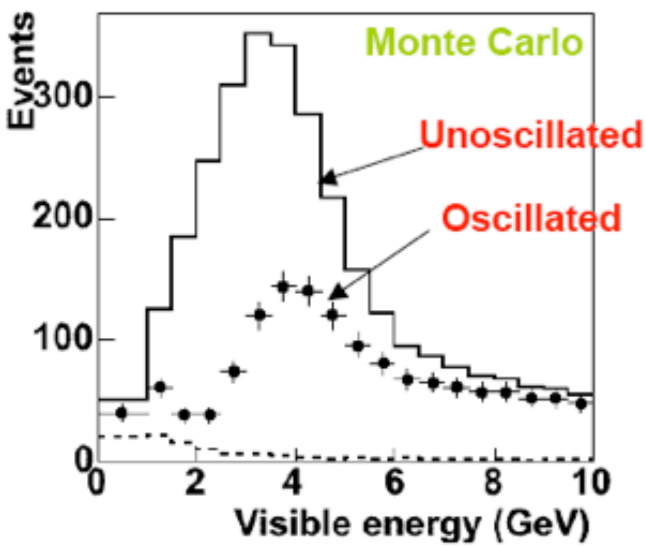
NuMI beam line

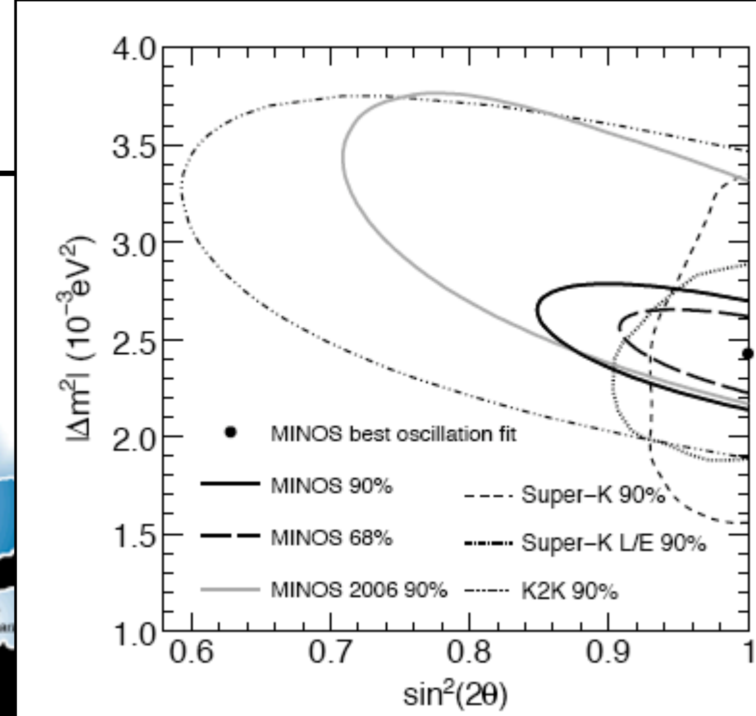


Precision Science with Accelerator ν



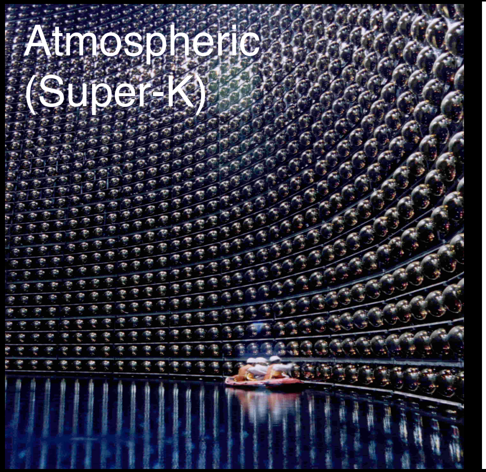
5.4 kton MINOS far detector

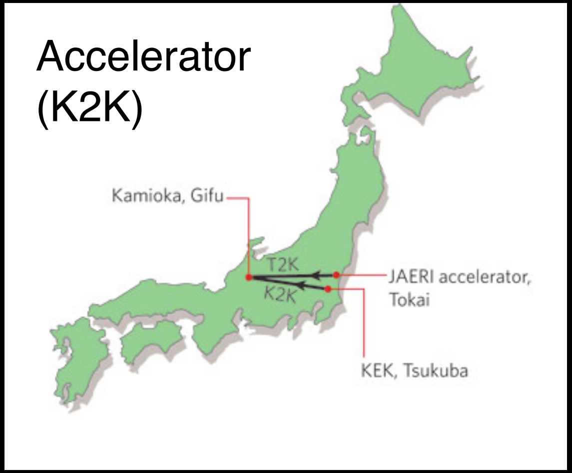


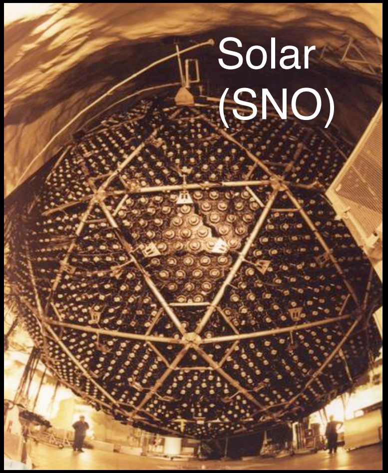


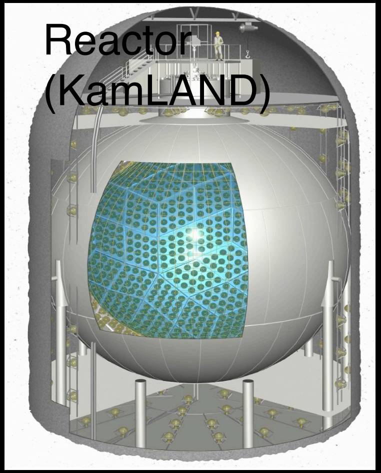
NuMI
beam line

A Decade of Discovery: 1998 - 2008

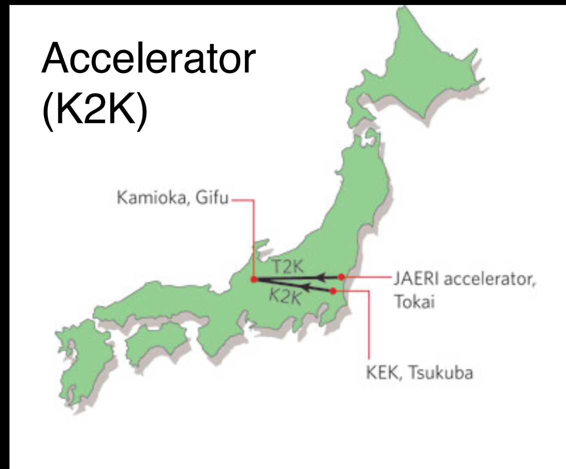


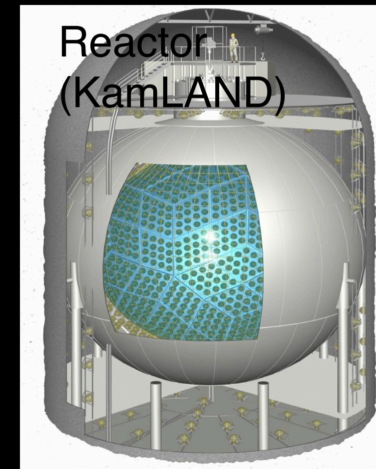






A Decade of Discovery: 1998 - 2008





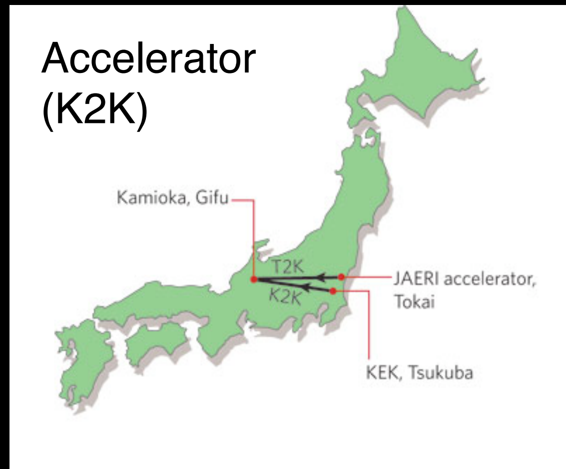
Super-K:
atmospheric ν_μ neutrino oscillation

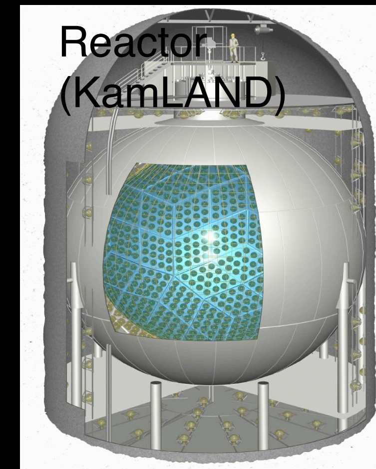
K2K:
accelerator ν_μ oscillation

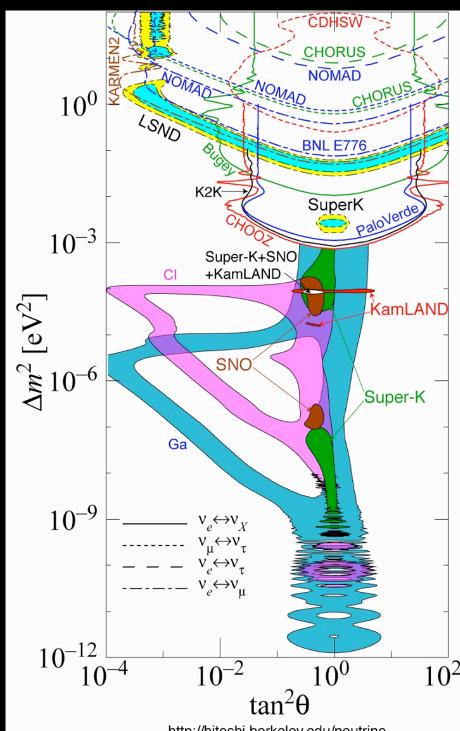
SNO:
solar ν_e flavor transformation

KamLAND:
reactor $\overline{\nu}_e$ disappearance and oscillation

A Decade of Discovery: 1998 - 2008







$$\nu_e \Leftrightarrow \nu_{\mu,\tau}$$

$$\nu_\mu \Leftrightarrow \nu_\tau$$

Super-K:
atmospheric ν_μ neutrino oscillation

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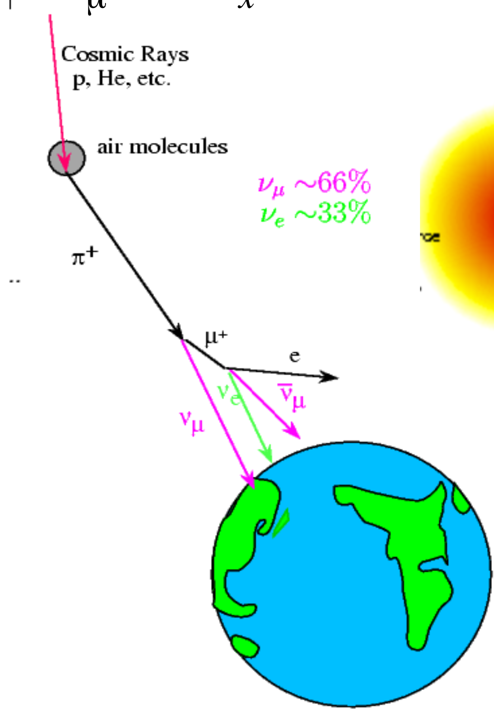
Experimental Indications for Neutrino Oscillations

Atmospheric Neutrinos

L = 15 - 15,000 km

E = 300 - 2000 MeV

$\nu_\mu \rightarrow \nu_x$



$\Delta m^2 = \sim 3 \times 10^{-3}\ eV^2$

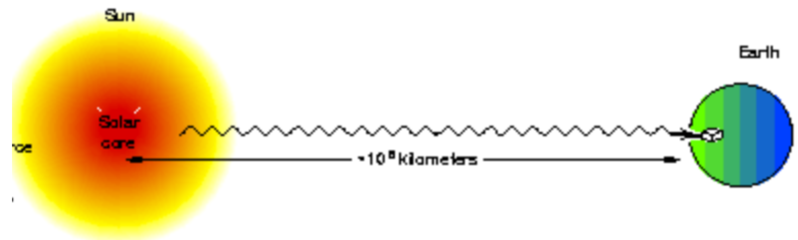
$\text{Prob}_{OSC} = \sim 100\%$

Solar Neutrinos

L = 10^8 km

E = 0.3 to 3 MeV

$\nu_e \rightarrow \nu_x$



$\Delta m^2 = \sim 5 \times 10^{-5}\ eV^2$

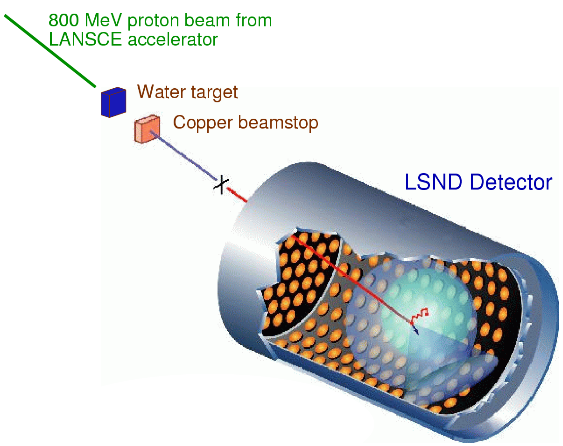
$\text{Prob}_{OSC} = \sim 100\%$

Experimental Indications for Neutrino Oscillations

LSND Experiment

L = 30m
E = ~40 MeV

$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$

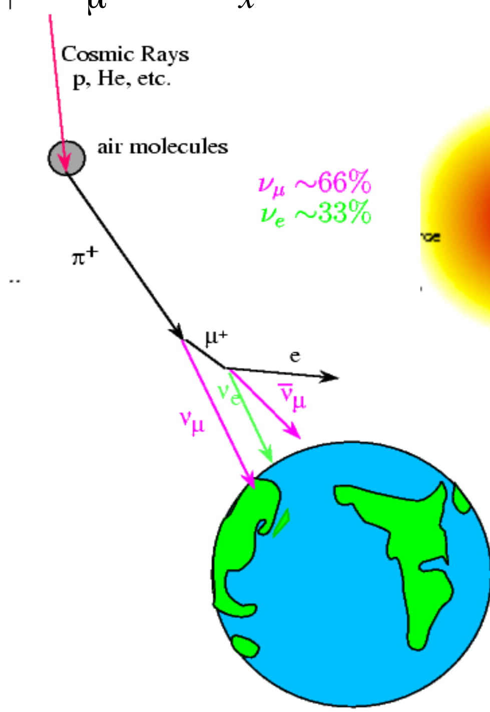


$\Delta m^2 = 0.3$ to $3\ eV^2$
$Prob_{OSC} = 0.3\ \%$

Atmospheric Neutrinos

L = 15 - 15,000 km
E = 300 - 2000 MeV

$\nu_\mu \rightarrow \nu_x$



$\Delta m^2 = \sim 3 \times 10^{-3}\ eV^2$
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Solar Neutrinos

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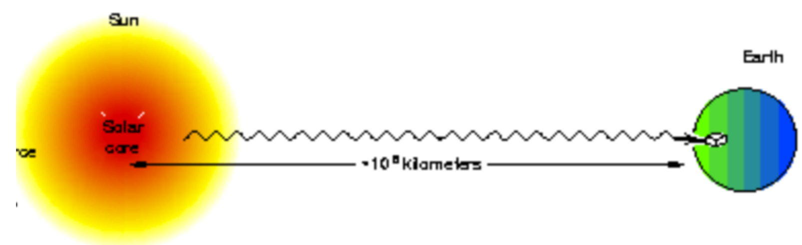
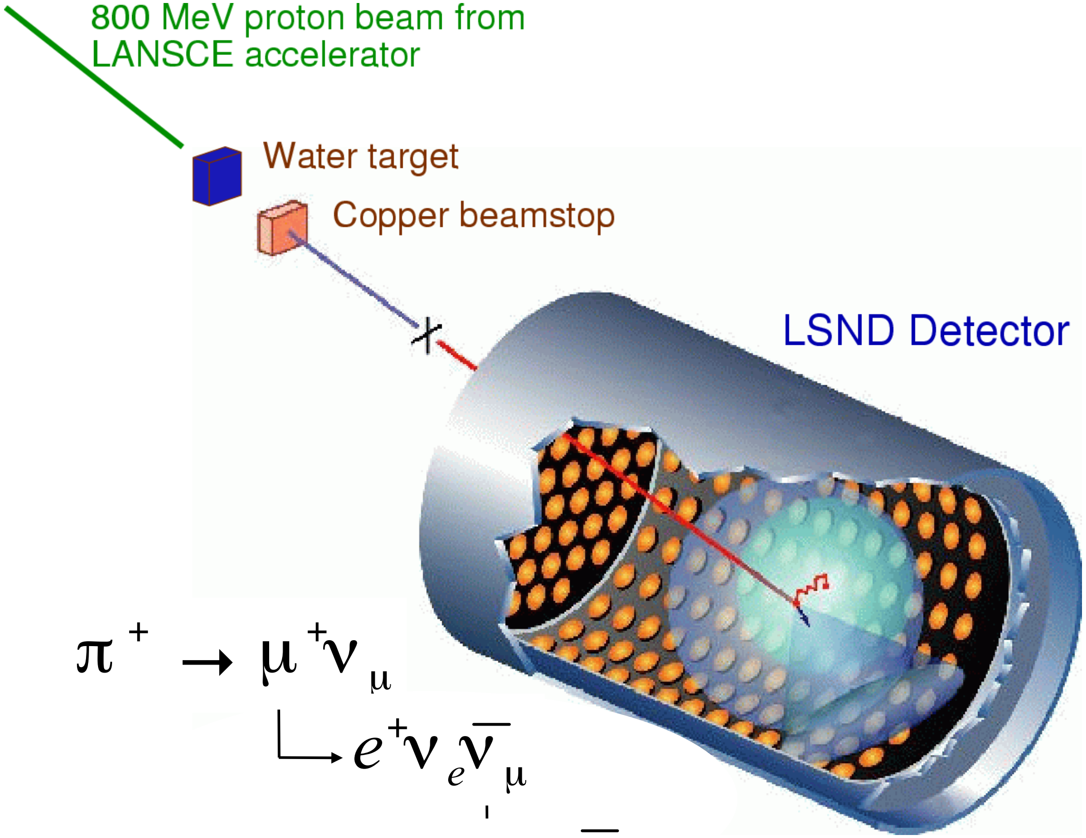


$\Delta m^2 = \sim 5 \times 10^{-5}\ eV^2$
$Prob_{OSC} = \sim 100\%$

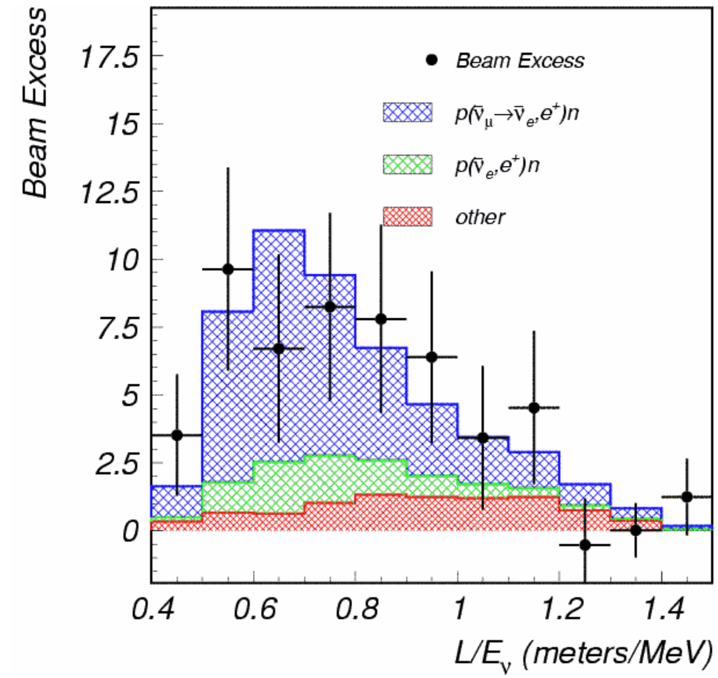
LSND Experiment



$\pi^+ \rightarrow \mu^+ \nu_\mu$

$\quad \hookrightarrow e^+ \nu_e \bar{\nu}_\mu$

Oscillations? $\rightarrow \bar{\nu}_e$



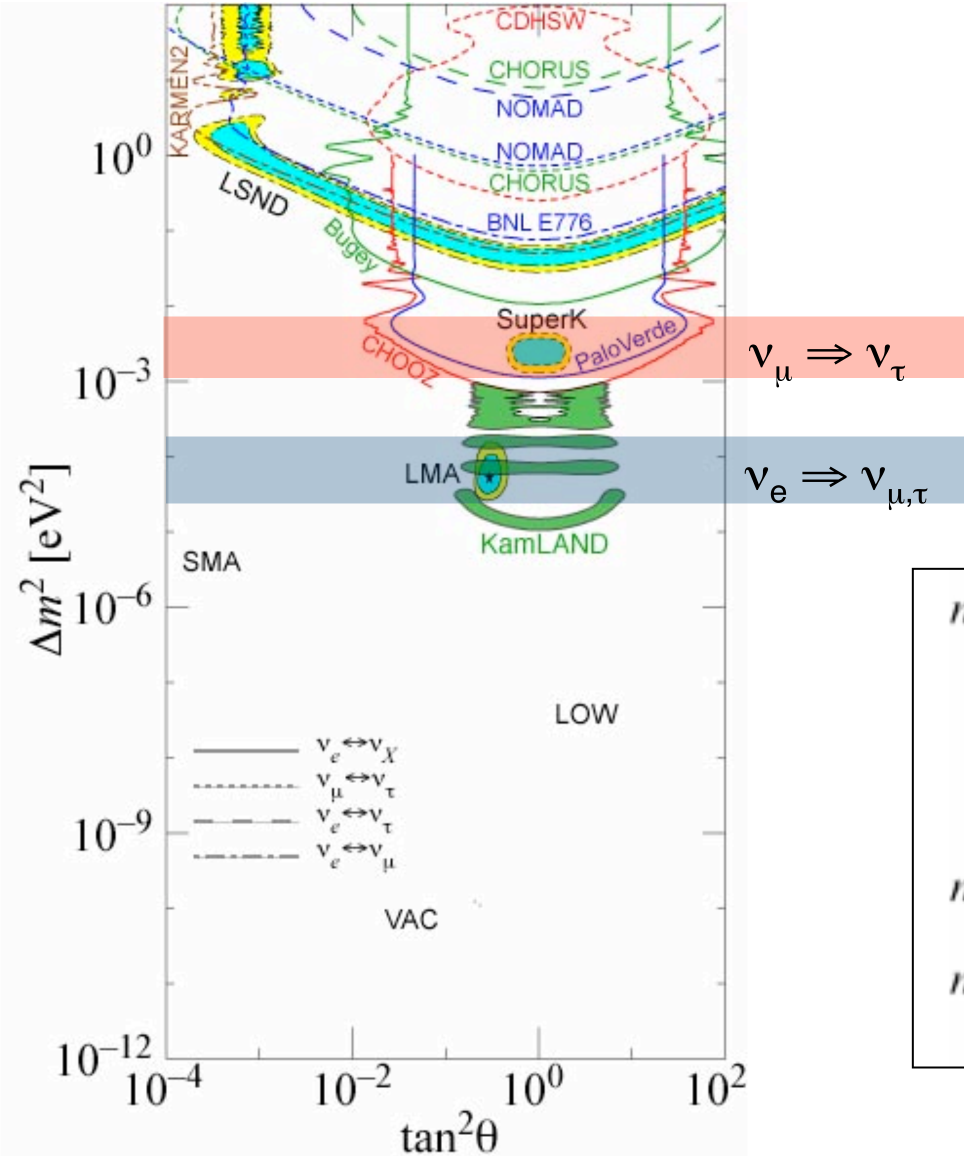
LSND took data from 1993-98
- 49,000 Coulombs of protons
- L = 30m and 20 < E_ν < 53 MeV

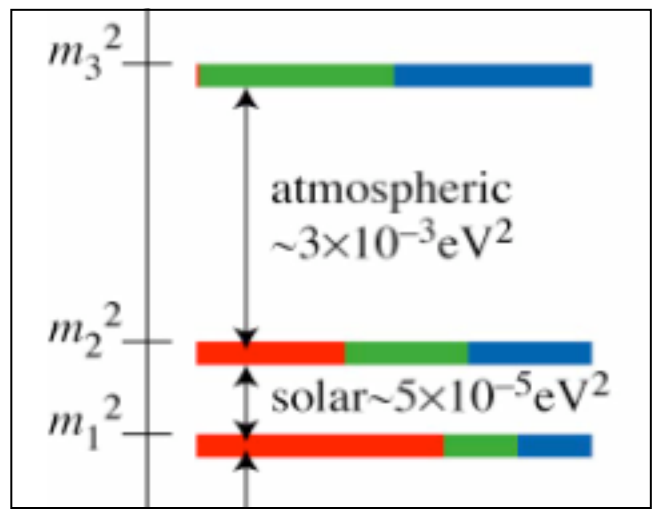
Saw an excess of:
87.9 ± 22.4 ± 6.0 events.

With an oscillation probability of
(0.264 ± 0.067 ± 0.045)%.

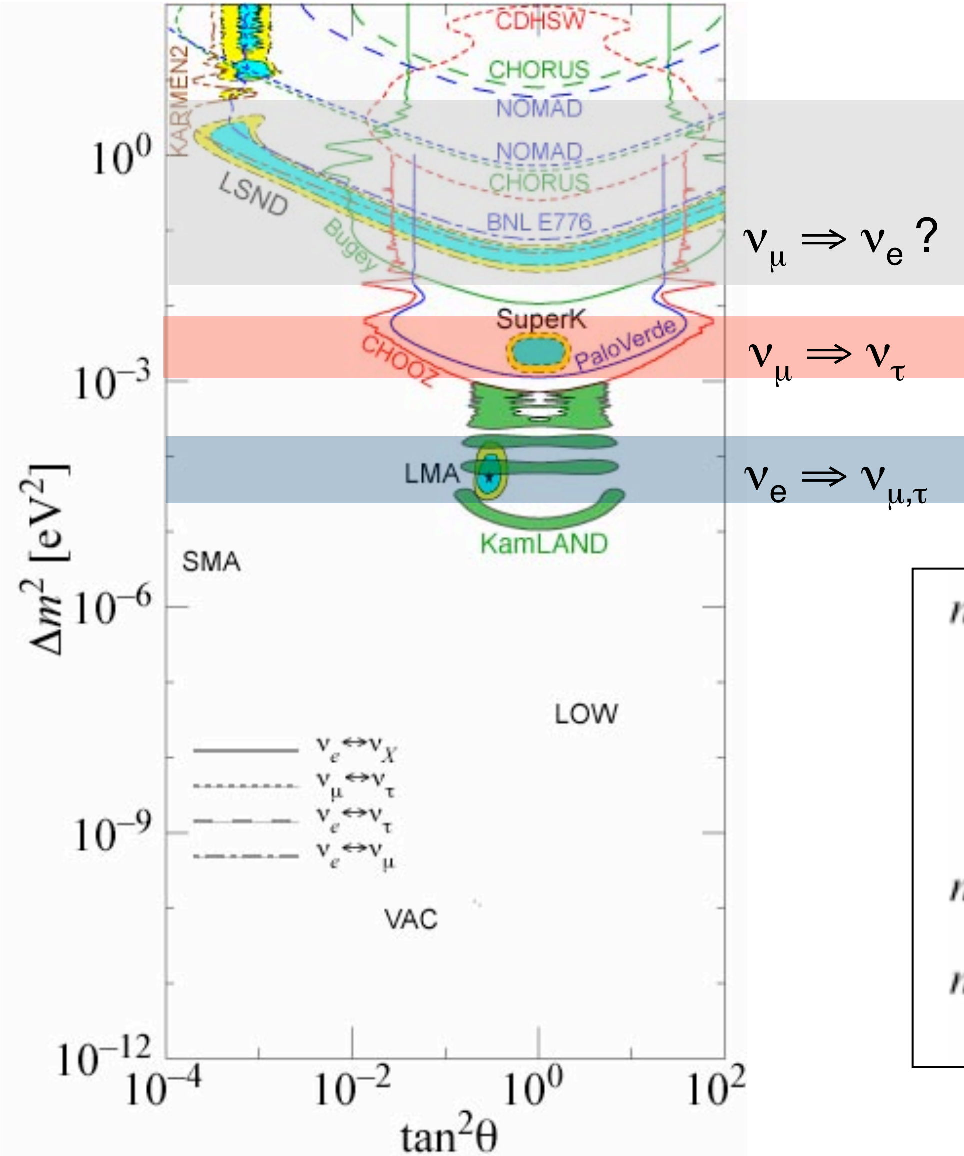
3.8 σ evidence for oscillation.

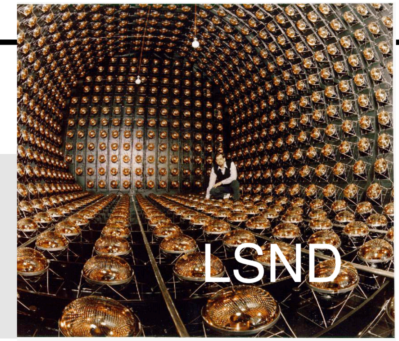
Other oscillations? Sterile Neutrinos?

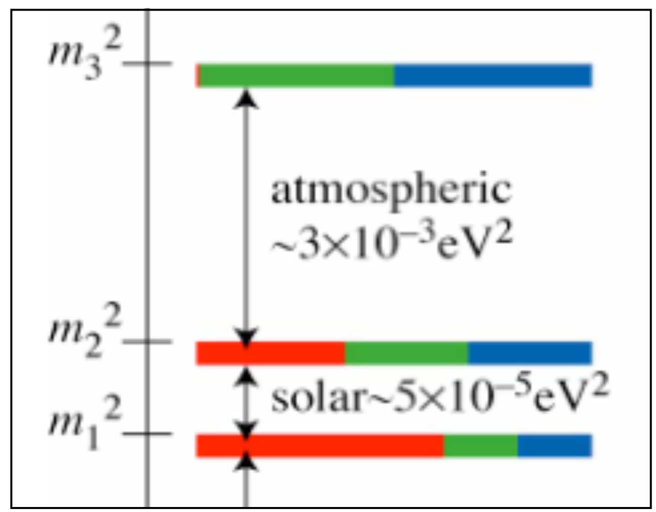




Other oscillations? Sterile Neutrinos?







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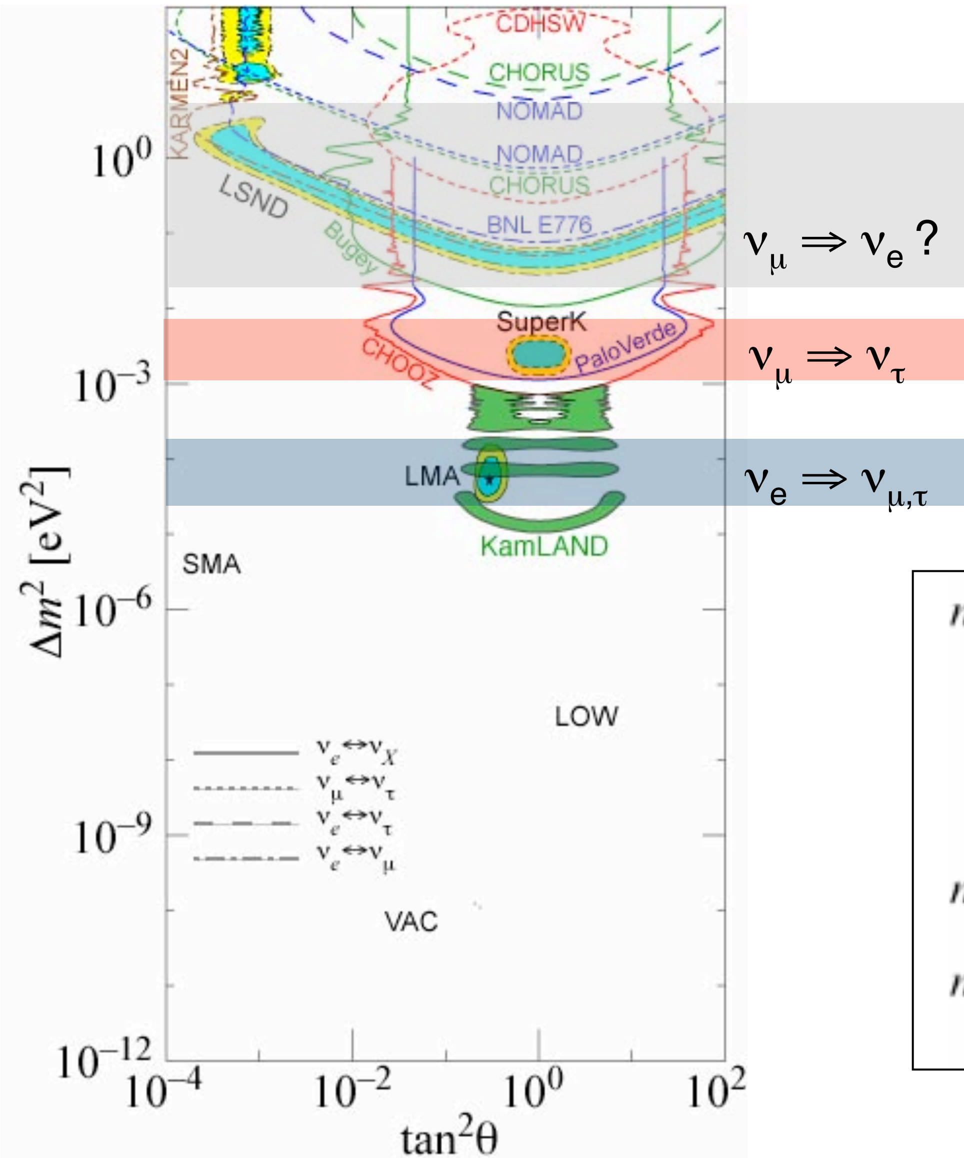
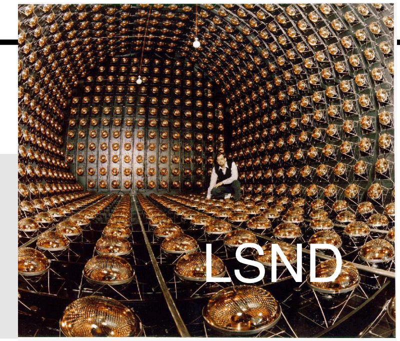
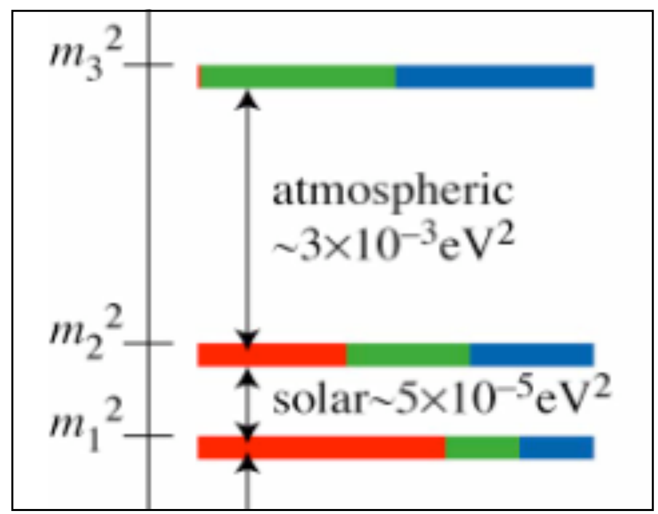


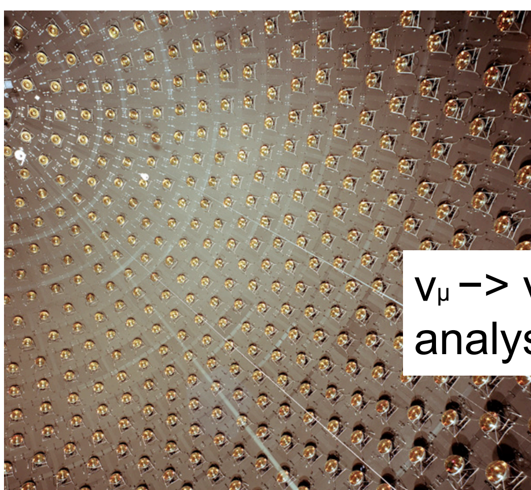


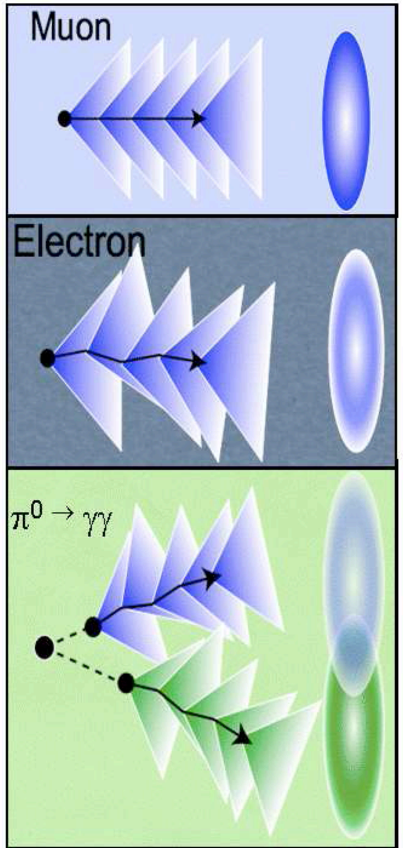
Cannot be explained by 3 active neutrinos!

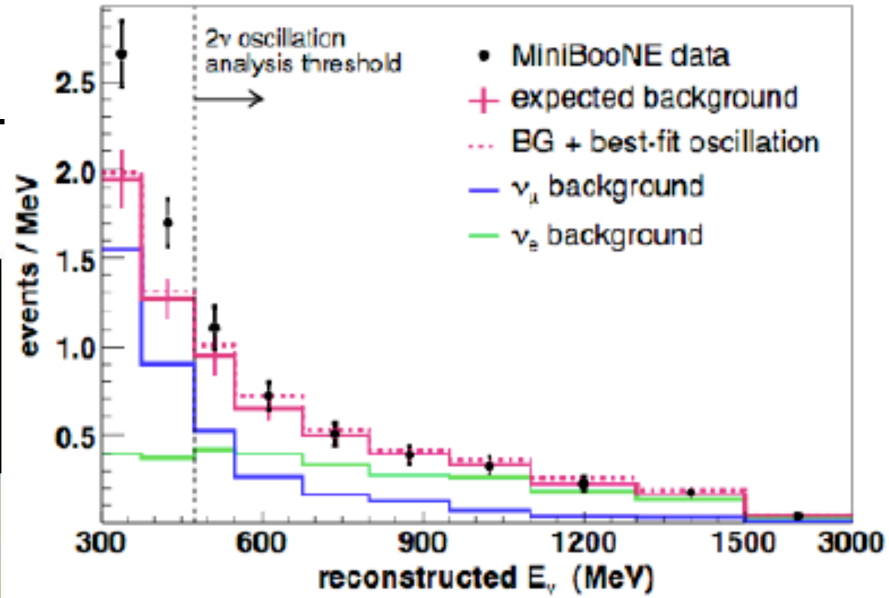


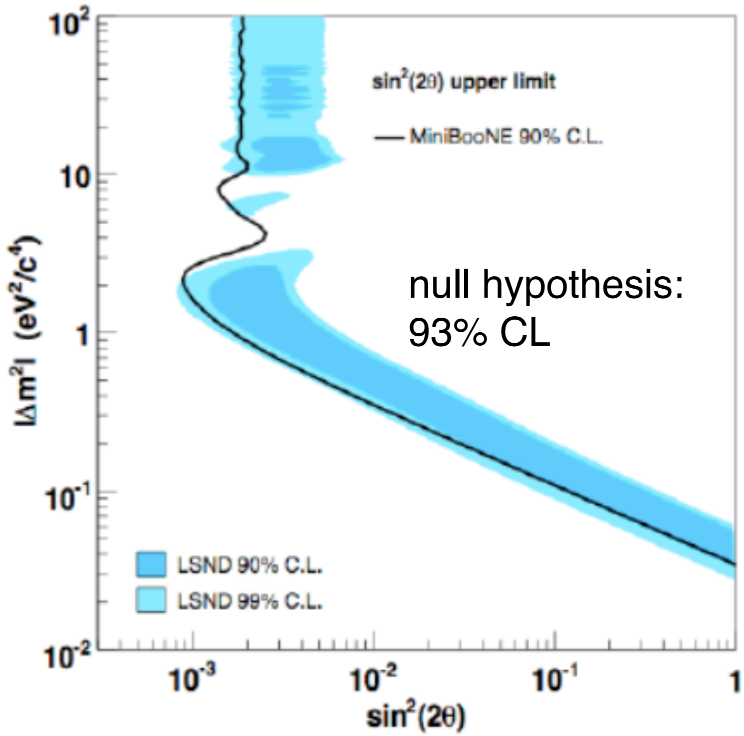
MiniBoone

- 1 GeV neutrinos (Booster)
- 800 ton oil Cerenkov
- operating since 2003
- $\nu_\mu \to \nu_e$ appearance









null hypothesis: 93% CL

$\nu_\mu \to \nu_e$ appearance only analysis is a limit on oscillation

Historical Lessons

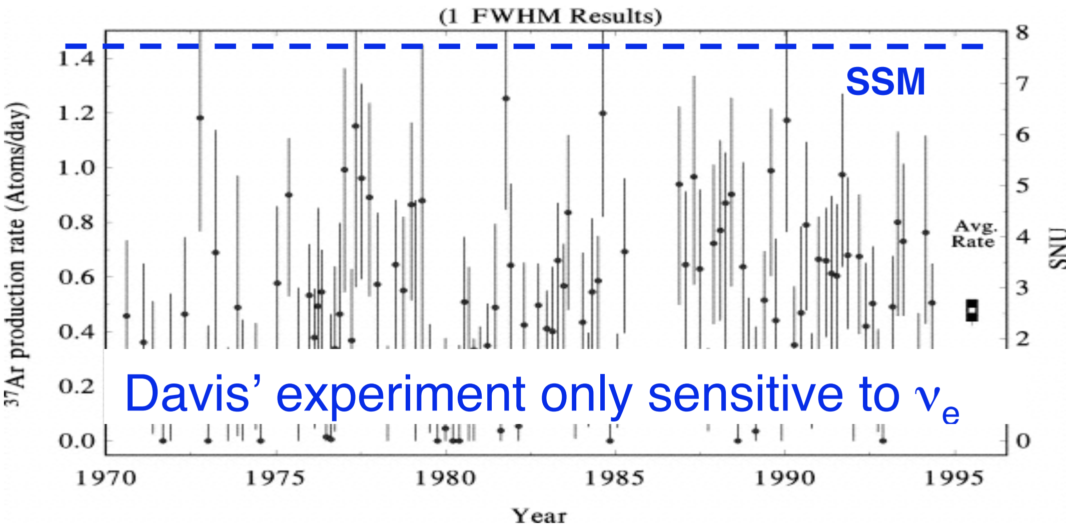
- *how did we make the discoveries?*

Historical Lessons

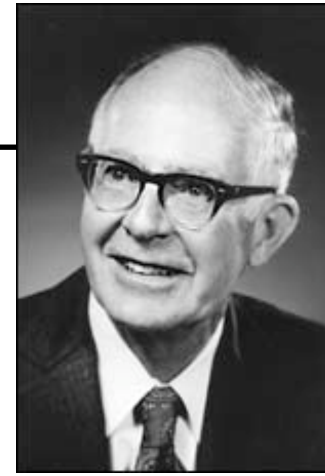
- how did we make the discoveries?

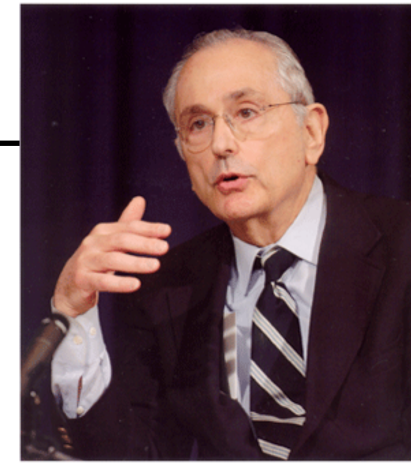
#1 persistence
#2 data “anomalies”, the unforeseen
#3 theorists aren’t (always) right
#4 unique, model-independent measurements
#5 big steps vs incremental improvements
#6 and a little bit of luck ... in detecting a supernova

#1 persistence

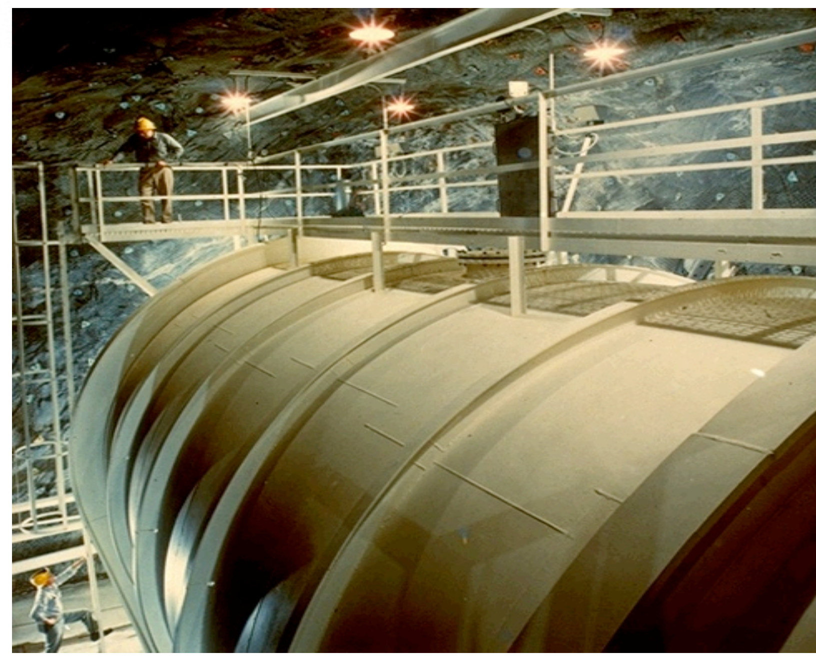


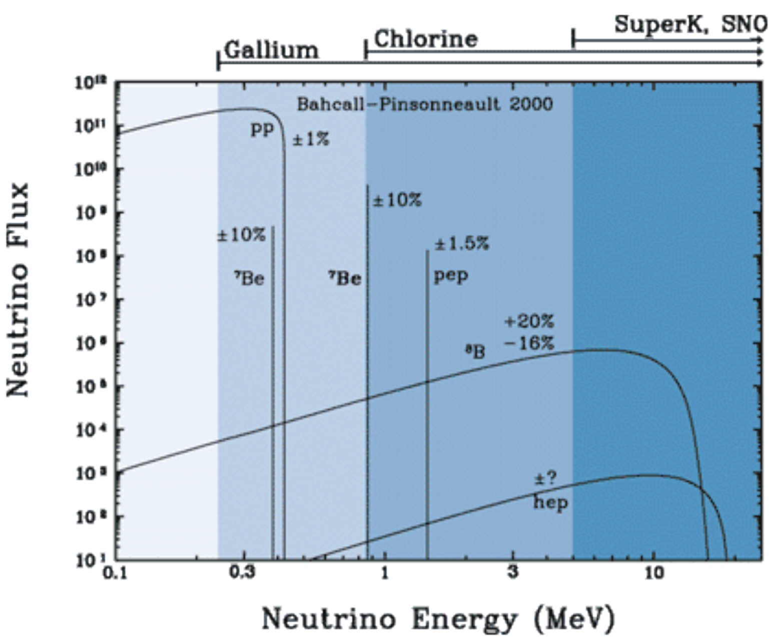
Davis' experiment only sensitive to ν_e





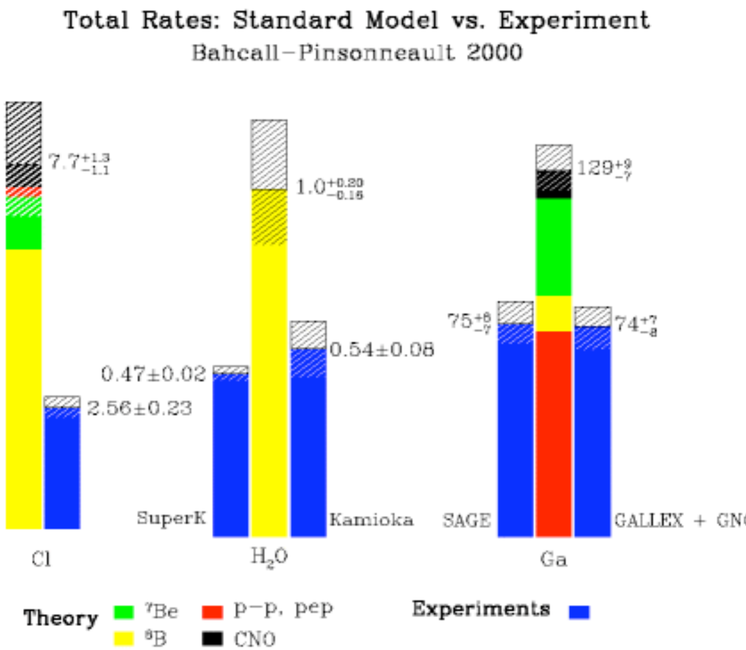
1970-1995

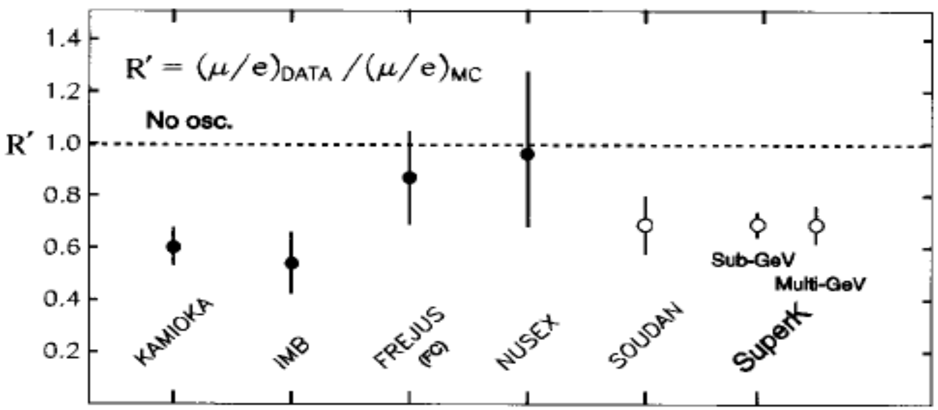




#2 “anomalies”

Solar Neutrino Problem

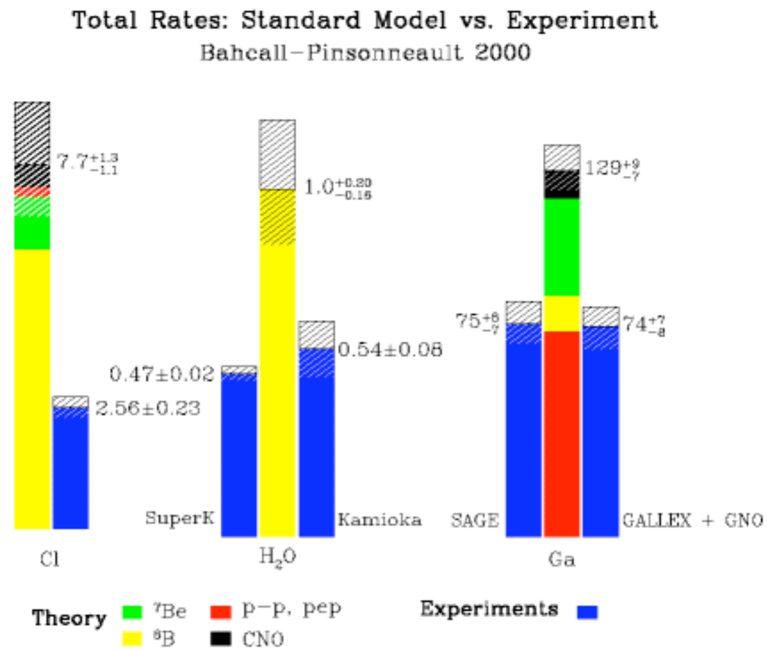


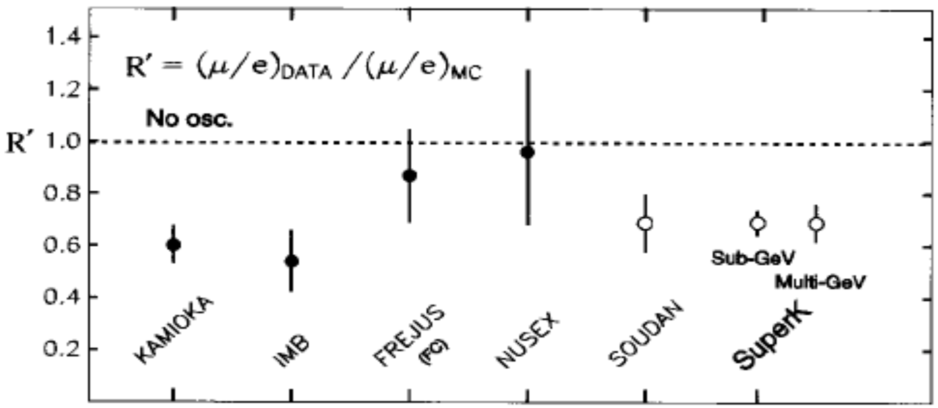


Atmospheric Neutrino Anomaly

#2 “anomalies”

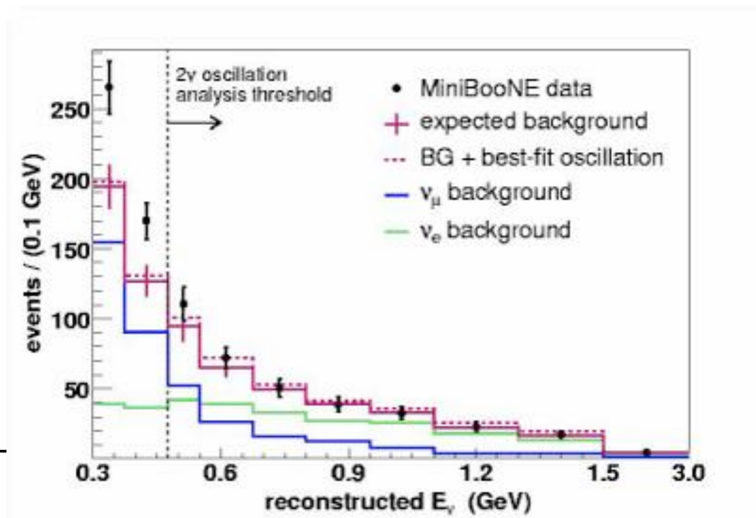
Solar Neutrino Problem





Atmospheric Neutrino Anomaly

Low-Energy Excess in MiniBoone?



#3 theorists aren't (always) right ...

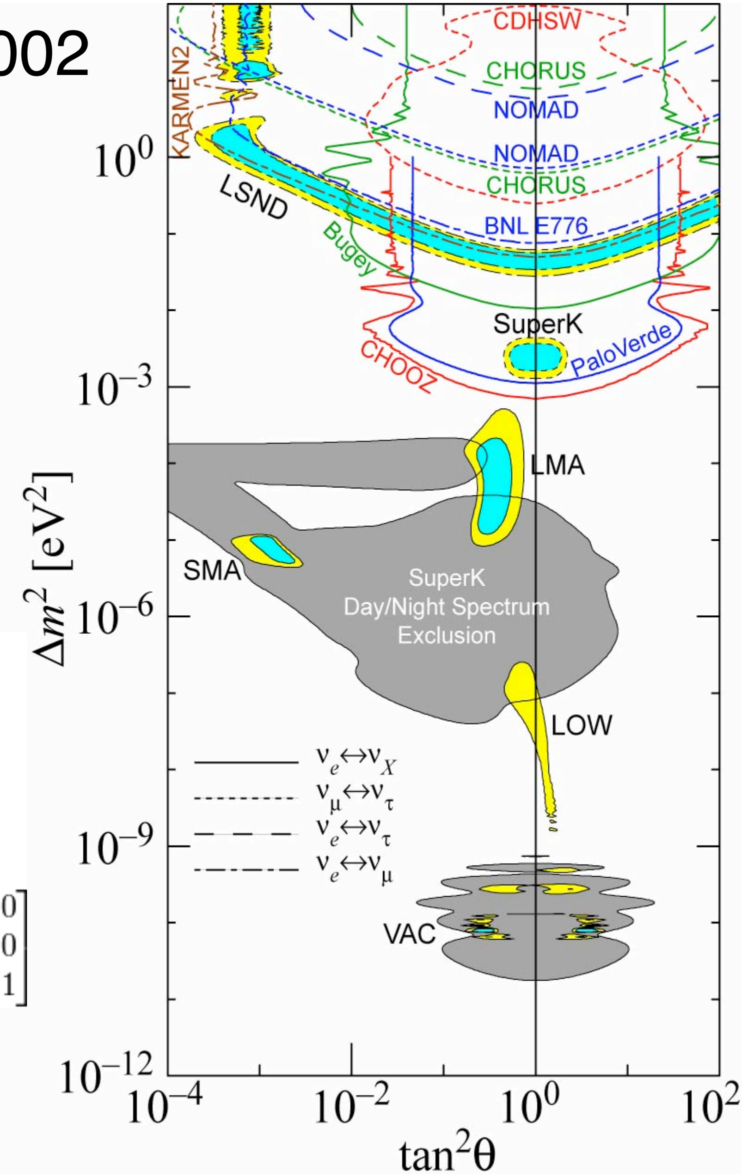
pre 2002

quark mixing

$$V_{CKM} = \begin{vmatrix} V_{ud} = 0.975 & V_{us} = 0.211 & V_{ub} = 0.005 \\ V_{cd} = 0.211 & V_{cs} = 0.974 & V_{cb} = 0.04 \\ V_{td} = 0.005 & V_{ts} = 0.041 & V_{tb} = 0.999 \end{vmatrix}$$

neutrino mixing

$$U = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix}$$
$$= \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$
$$= \begin{bmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{bmatrix} \begin{bmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$



#3 theorists aren't (always) right ...

"Oscillation mixing angles must be small like the quark mixing angles"

"Atmospheric neutrino anomaly must be other physics or experimental problem because it needs such a large mixing angle"

"Natural scale for $\Delta m^2 \sim 10 - 100$ eV^2 since needed to explain dark matter"

"LSND result doesn't fit in so must not be an oscillation signal"

#3 theorists aren’t (always) right ...

“Oscillation mixing angles must be small like the quark mixing angles” Wrong

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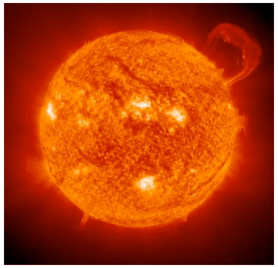
“Natural scale for $\Delta m^2 \sim 10 - 100$ eV^2 since needed to explain dark matter” Wrong

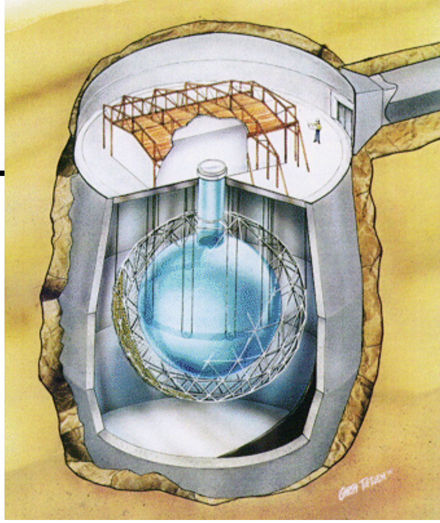
“LSND result doesn’t fit in so must not be an oscillation signal” ???

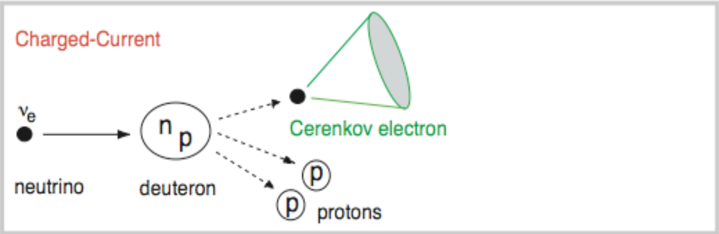
#4 unique, model-independent measurements

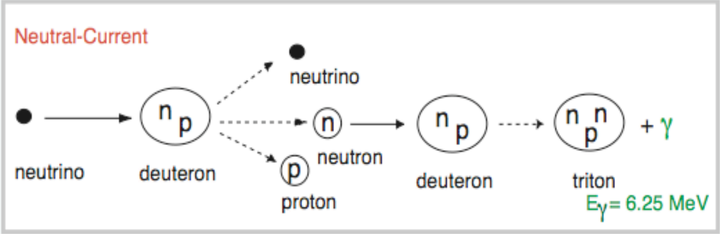


a pure ν_e source

a ν_x detector







Charged-Current (CC)

$\nu_e + d \rightarrow e^- + p + p$

Neutral-Current (NC)

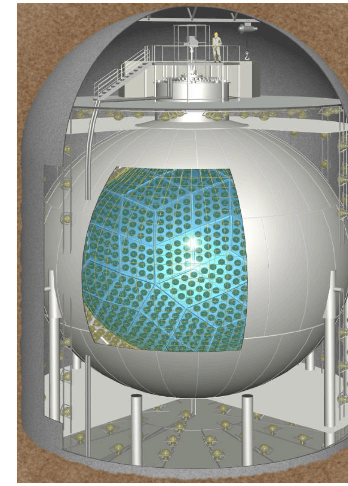
$\nu_x + d \rightarrow \nu_x + n + p$

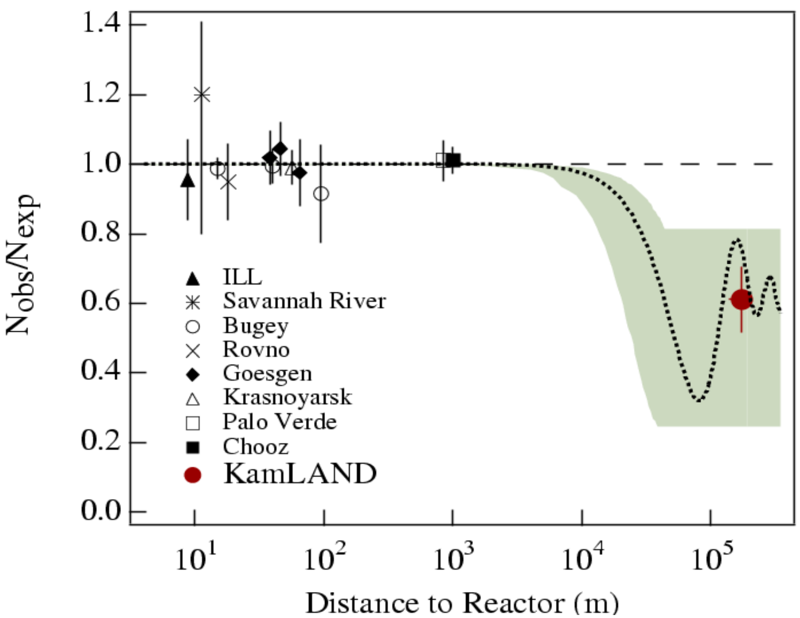
- eliminate model-dependent assumptions and interpretation
- physics result independent of Monte Carlo
- any result from SNO would have been interesting: win-win situation!

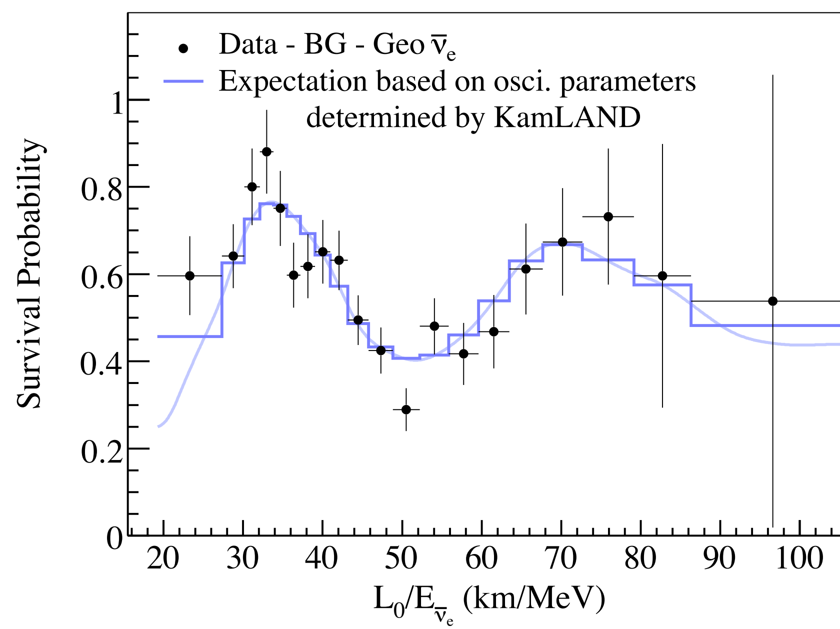
#5 taking big steps

baseline: 1 km → 180 km

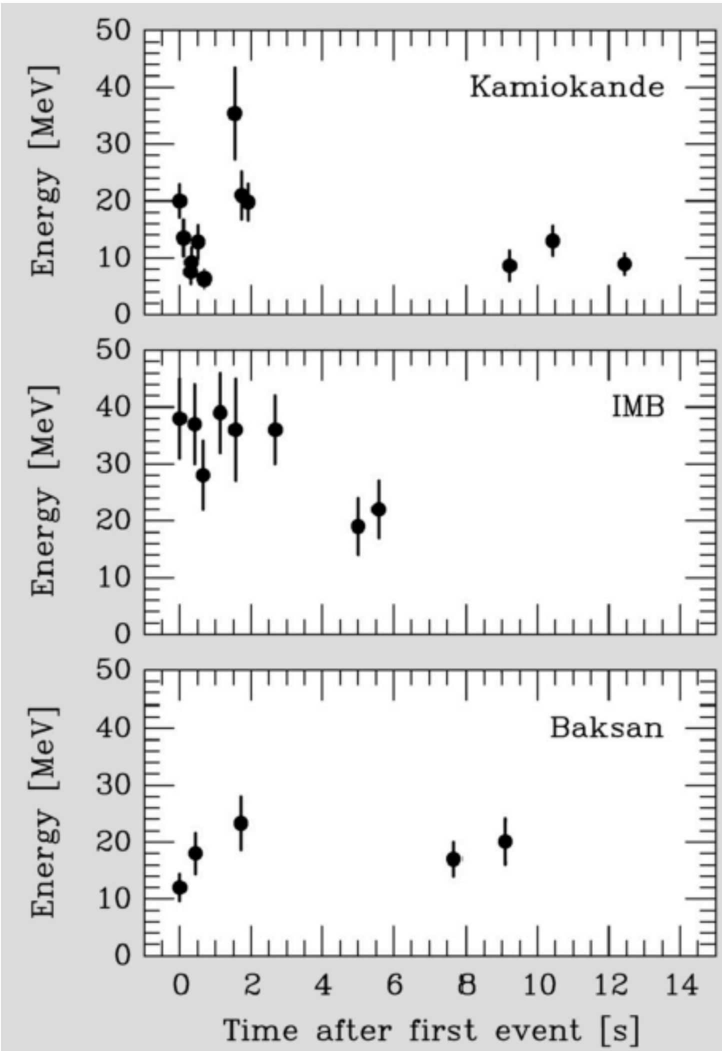
size: 5 ton → 1000 ton



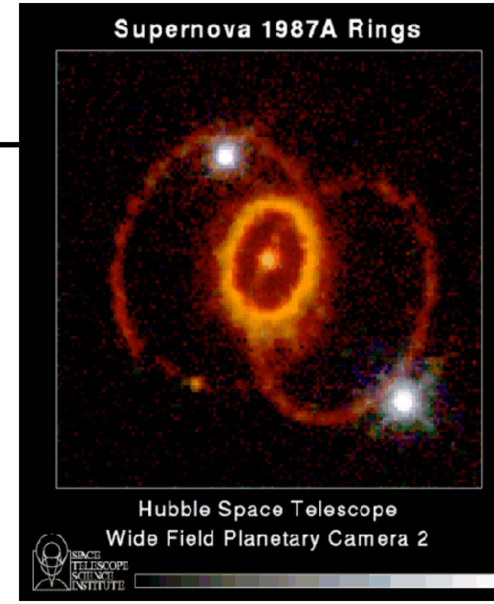




#6 and a little bit of luck...in detecting a SN



Supernova 1987A



Nobel Prize for the Detection of Cosmic Neutrinos

- **The Nobel Prize in Physics**

  "for pioneering contributions to astrophysic
  in particular for the detection of cosmic
  neutrinos"

  Raymond Davis Jr.
  USA

  Masatoshi Koshiba
  Japan

Raymond Davis Jr.

Masatoshi Koshiba

Kamiokande was ready to seize the opportunity

Future Efforts

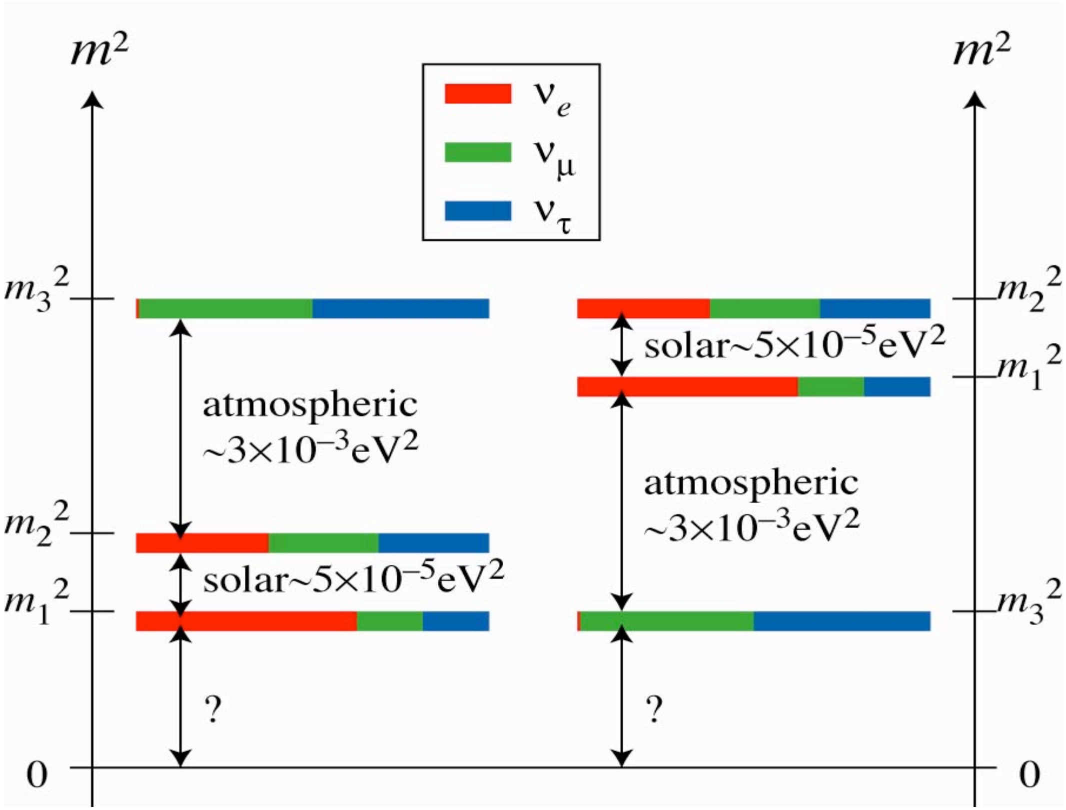
- from discoveries to precision studies, picking the best tools at hand

- what are the future directions of neutrino physics?

- neutrinos in particle/astrophysics

What we know...

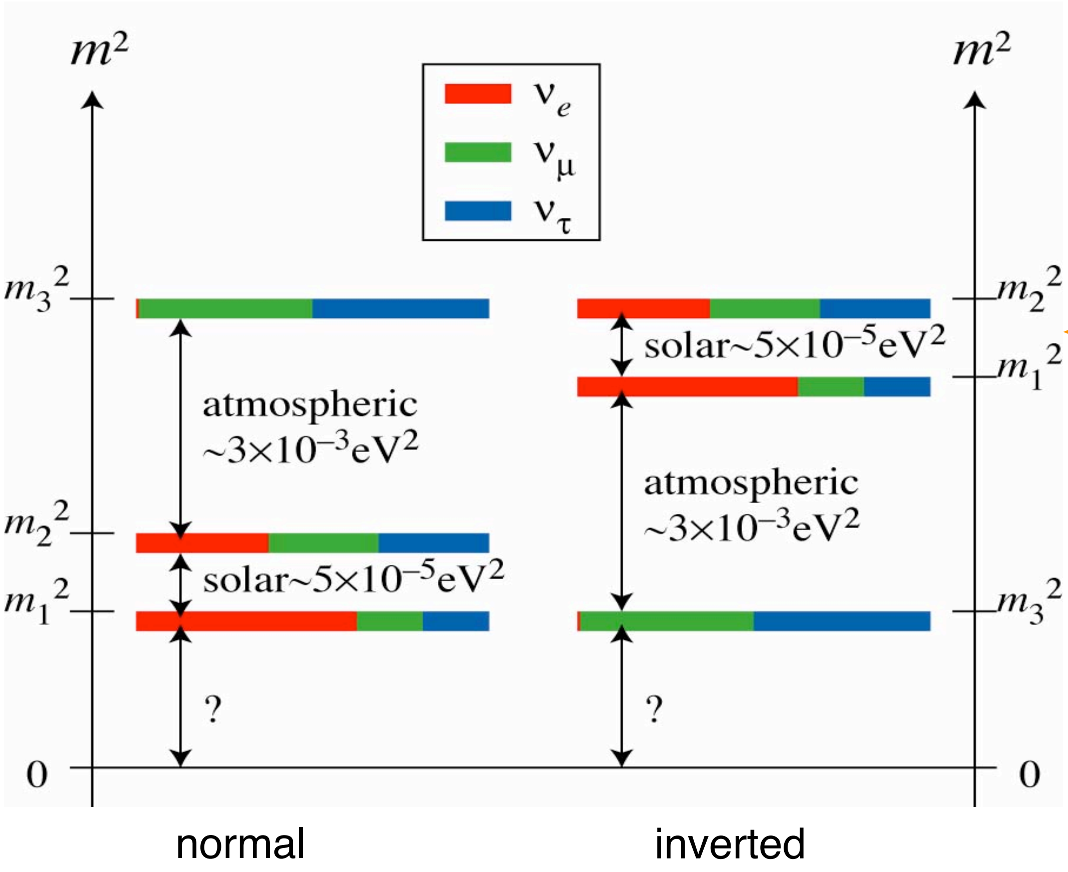
Neutrino Mass Splitting



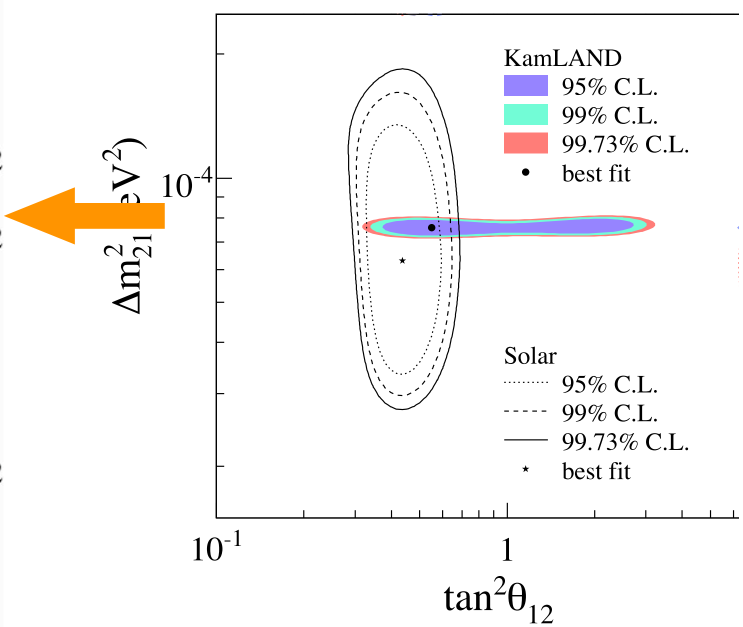
normal inverted

What we know...

Neutrino Mass Splitting



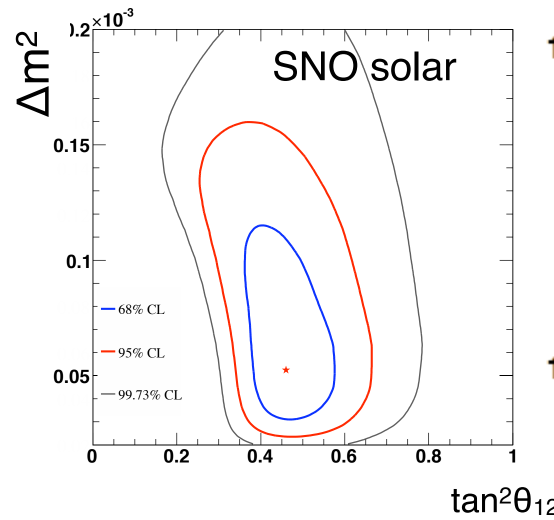
KamLAND 2008

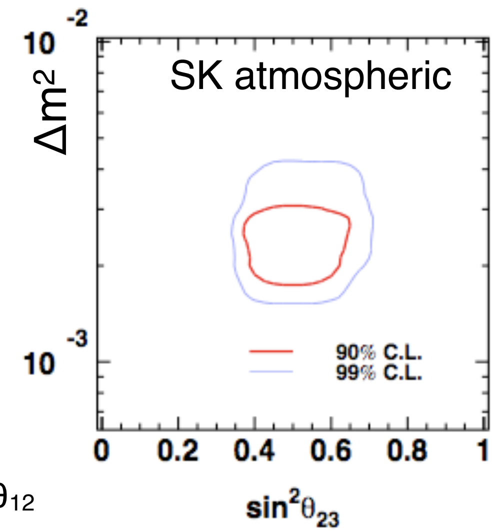


- KamLAND provides most precise value of Δm_{12}^2 (~2.8%)

What we know...

Neutrino Mixing Angles





$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} = \begin{pmatrix} 0.8 & 0.5 & U_{e3} \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix}$$

U_{MNSP} Matrix

Maki, Nakagawa, Sakata, Pontecorvo

$$= \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix}} \times \underbrace{\begin{pmatrix} \cos\theta_{13} & 0 & e^{-i\delta_{CP}}\sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{i\delta_{CP}}\sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix}} \times \underbrace{\begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}} \times \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha/2} & 0 \\ 0 & 0 & e^{i\alpha/2+i\beta} \end{pmatrix}}$$

atmospheric, K2K — reactor and accelerator — SNO, solar SK, KamLAND — $0\nu\beta\beta$

$\theta_{23} = \sim 45°$ — $\theta_{13} = ?$ — $\theta_{12} \sim 32°$

What we know...

Neutrino Mixing Angles

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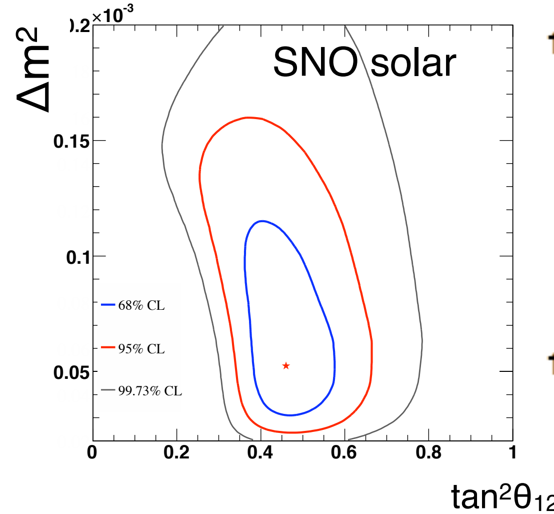

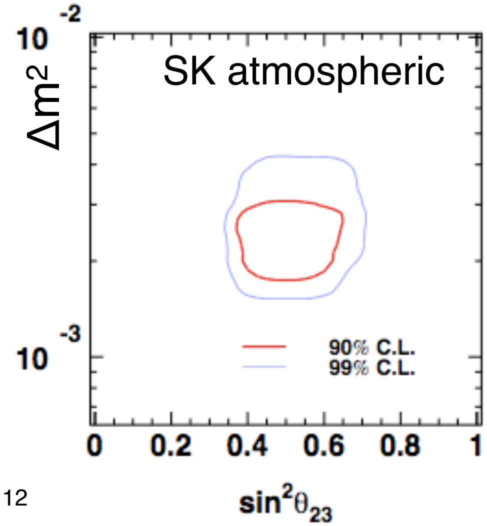

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$\theta_{23} = \sim 45°$ — maximal?

$\theta_{13} = ?$

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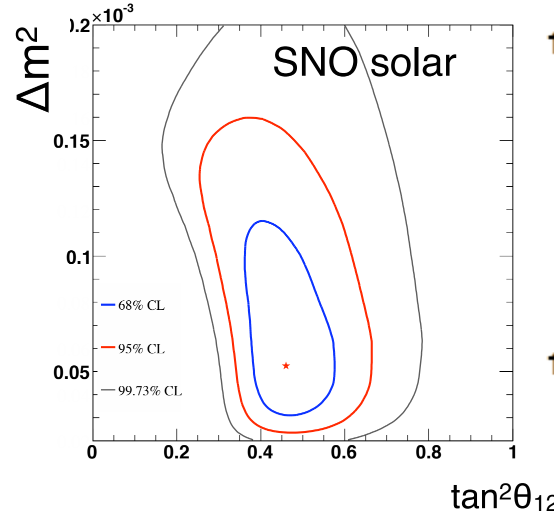
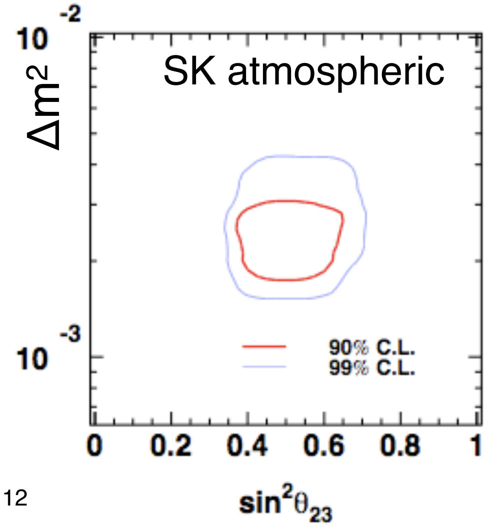
What we know...

Neutrino Mixing Angles





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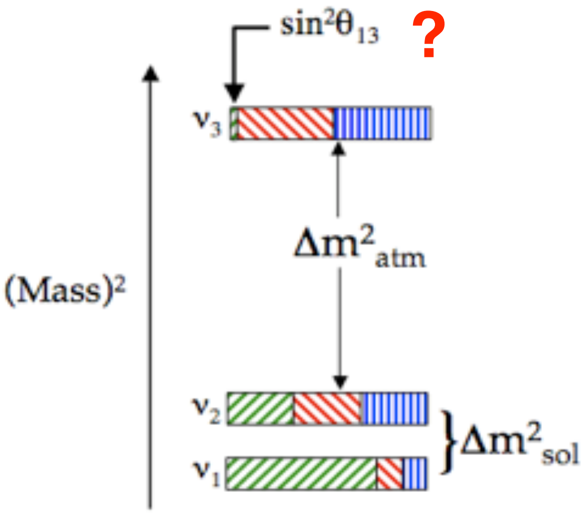
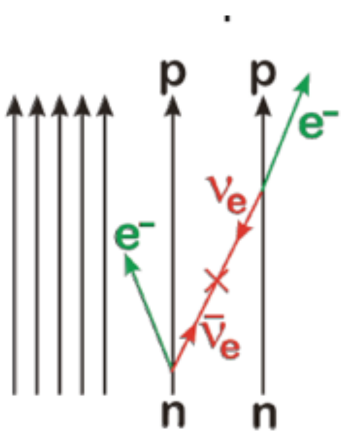
Open Questions

$$P(\nu_\mu \rightarrow \nu_e) - P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) = -16 s_{12} c_{12} s_{13} c_{13}^2 s_{23} c_{23}$$
$$\sin\delta \sin\left(\frac{\Delta m_{12}^2}{4E} L\right) \sin\left(\frac{\Delta m_{13}^2}{4E} L\right) \sin\left(\frac{\Delta m_{23}^2}{4E} L\right)$$





Questions

Is there μ–τ symmetry in neutrino mixing?

Is there leptonic CPV?

What is mass hierarchy?

Do neutrinos have Majorana mass?

What is the absolute mass scale?

What is the role of neutrinos in the Universe?

Open Questions

The Tools

reactor & accelerator experiments

search for $0\nu\beta\beta$

β-decay experiments

astrophysics & cosmology

➡

Questions

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Neutrino Sources

Neutrinos from the Big Bang

~330 neutrinos per cm^3

0.5 proton per cm^3

Supernova Neutrinos

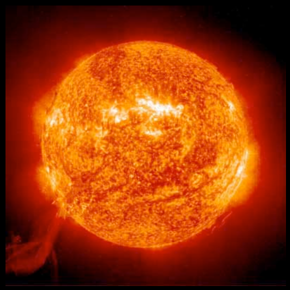
Atmospheric Neutrinos

High Energy Cosmic Neutrinos

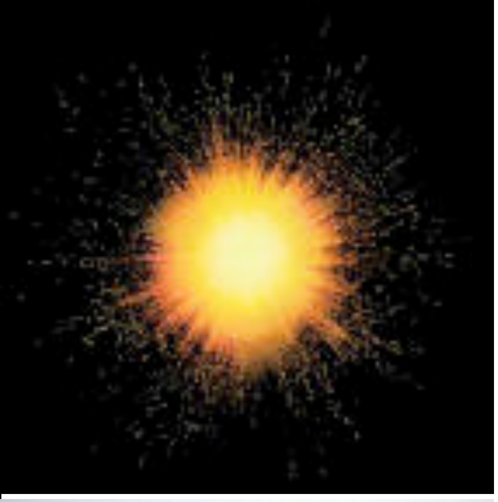
Geo Neutrinos

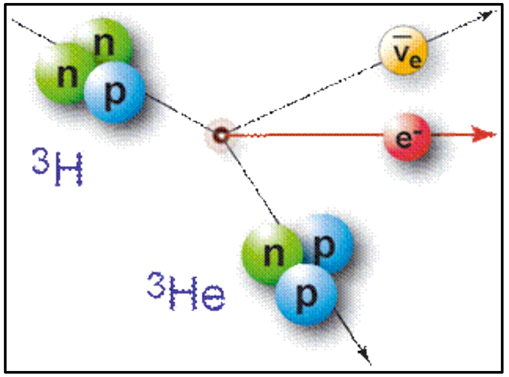
Accelerator&Reactor Neutrinos

Solar Neutrinos

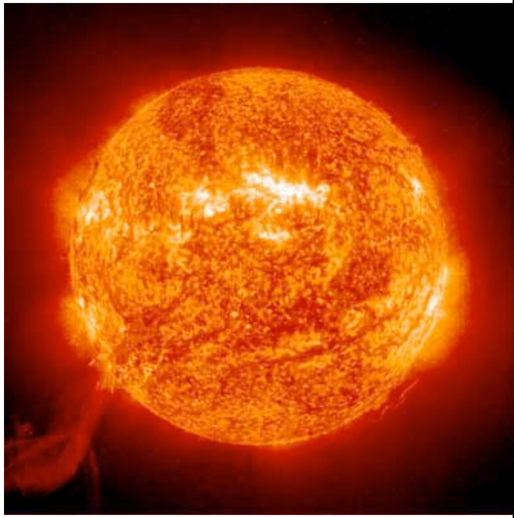


Neutrino Energies





Big-Bang neutrinos ~ 0.0004 eV



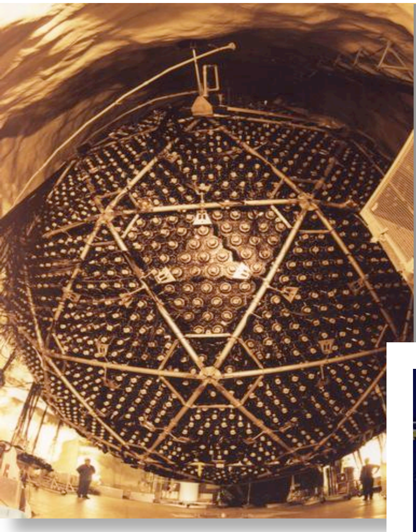
Neutrinos from the Sun < 20 MeV
depending of their origin.

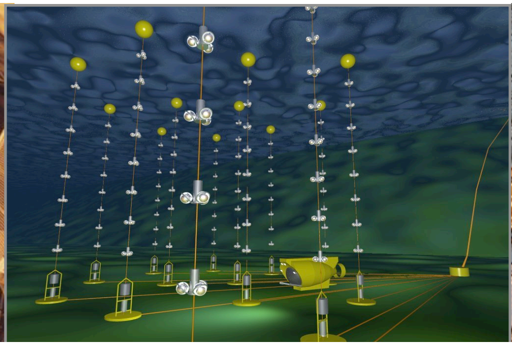
Antineutrinos from nuclear reactors < 10.0 MeV

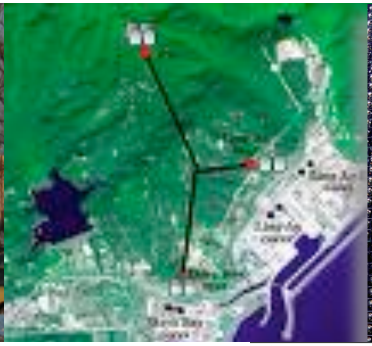
Atmospheric neutrinos ~ GeV

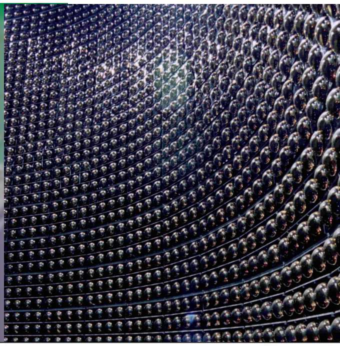
Neutrinos from accelerators up to GeV (10^9 eV)

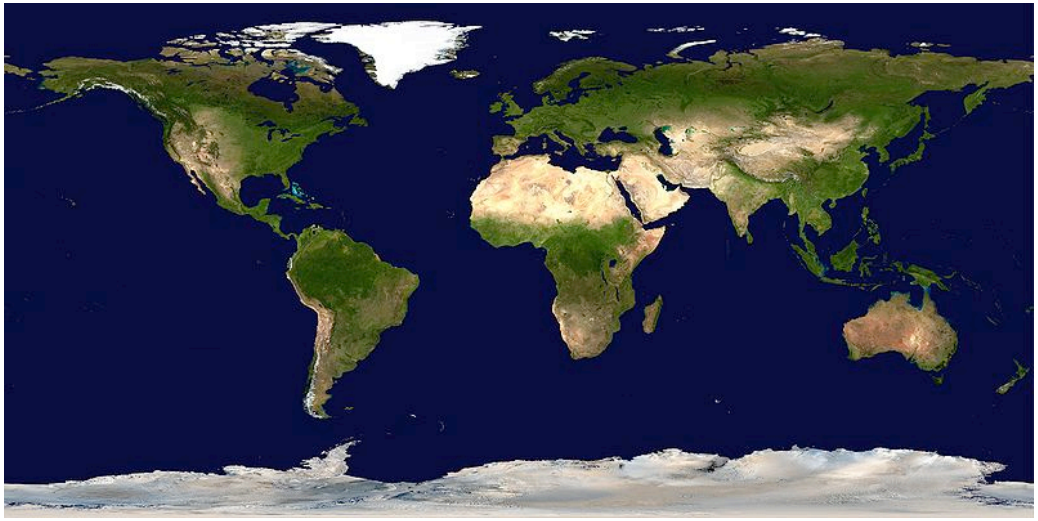
A World of Neutrino Detectors

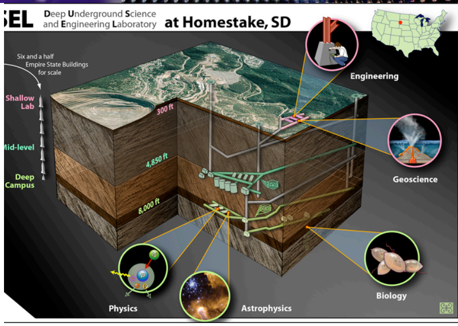


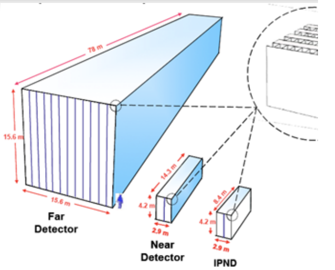


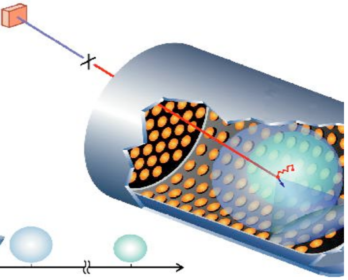


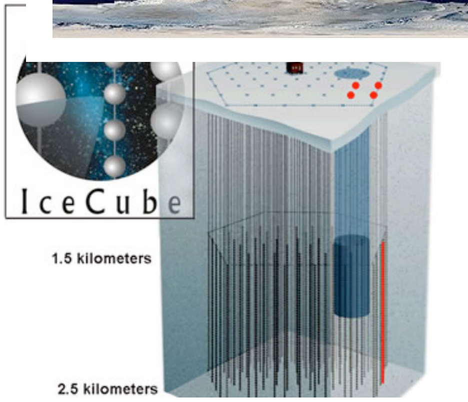


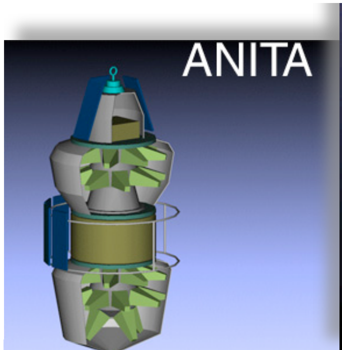


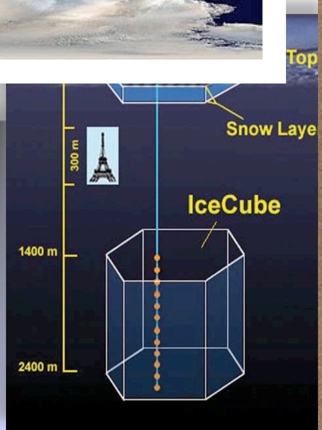


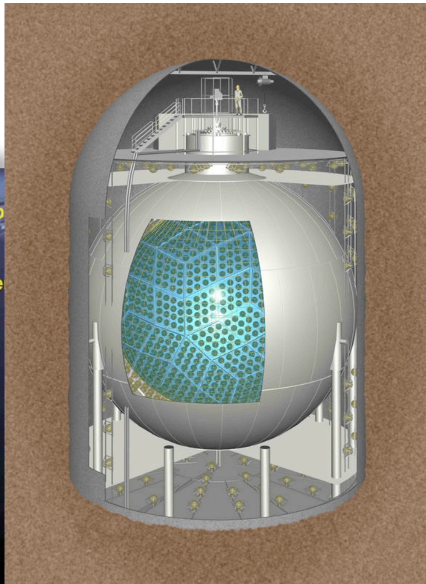












Reactor and Accelerator Experiments

reactor ($\bar{\nu}_e$ disappearance)

$$P_{ee} \approx 1 - \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m_{31}{}^2 L}{4E_\nu}\right) - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\left(\frac{\Delta m_{21}{}^2 L}{4E_\nu}\right)$$

- Clean measurement of θ_{13}
- No matter effects

accelerator (ν_e appearance)

$$\begin{aligned} P(\nu_\mu \to \nu_e) &= 4c_{13}^2 s_{13}^2 s_{23}^2 \sin^2\Delta_{31} \\ &+ 8c_{13}^2 s_{13} s_{23} c_{23} s_{12} c_{12} \sin\Delta_{31}\left[\cos\Delta_{32}\cos\delta - \sin\Delta_{32}\sin\delta\right]\sin\Delta_{21} \\ &- 8c_{13}^2 s_{13}^2 s_{23}^2 s_{12}^2 \cos\Delta_{32}\sin\Delta_{31}\sin\Delta_{21} \\ &+ 4c_{13}^2 s_{12}^2\left[c_{12}^2 c_{23}^2 + s_{12}^2 s_{23}^2 s_{13}^2 - 2c_{12}c_{23}s_{12}s_{23}s_{13}\cos\delta\right]\sin^2\Delta_{21} \\ &- 8c_{13}^2 s_{13}^2 s_{23}^2 (1 - 2s_{13}^2)\frac{aL}{4E_\nu}\sin\Delta_{31}\left[\cos\Delta_{32} - \frac{\sin\Delta_{31}}{\Delta_{31}}\right] . \end{aligned}$$

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accelerator (ν_e appearance)

matter

$$\begin{aligned} P(\nu_\mu \to \nu_e) = {} & 4c_{13}^2 s_{13}^2 s_{23}^2 \sin^2\Delta_{31} \\ & + 8c_{13}^2 s_{13} s_{23} c_{23} s_{12} c_{12} \sin\Delta_{31} [\cos\Delta_{32}\cos\delta - \sin\Delta_{32}\sin\delta] \sin\Delta_{21} \\ & - 8c_{13}^2 s_{13}^2 s_{23}^2 s_{12}^2 \cos\Delta_{32} \sin\Delta_{31} \sin\Delta_{21} \\ & + 4c_{13}^2 s_{12}^2 [c_{12}^2 c_{23}^2 + s_{12}^2 s_{23}^2 s_{13}^2 - 2c_{12} c_{23} s_{12} s_{23} s_{13} \cos\delta] \sin^2\Delta_{21} \\ & - 8c_{13}^2 s_{13}^2 s_{23}^2 (1 - 2s_{13}^2) \frac{aL}{4E_\nu} \sin\Delta_{31} \left[\cos\Delta_{32} - \frac{\sin\Delta_{31}}{\Delta_{31}}\right] . \end{aligned}$$

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mass hierarchy

accelerator (ν_e appearance)

matter

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mass hierarchy

CP violation

matter

accelerator (ν_e appearance)

$$\begin{aligned} P(\nu_\mu \to \nu_e) = {} & 4c_{13}^2 s_{13}^2 s_{23}^2 \sin^2\Delta_{31} \\ & + 8c_{13}^2 s_{13} s_{23} c_{23} s_{12} c_{12} \sin\Delta_{31} [\cos\Delta_{32}\cos\delta - \sin\Delta_{32}\sin\delta] \sin\Delta_{21} \\ & - 8c_{13}^2 s_{13}^2 s_{23}^2 s_{12}^2 \cos\Delta_{32} \sin\Delta_{31} \sin\Delta_{21} \\ & + 4c_{13}^2 s_{12}^2 [c_{12}^2 c_{23}^2 + s_{12}^2 s_{23}^2 s_{13}^2 - 2c_{12}c_{23}s_{12}s_{23}s_{13}\cos\delta] \sin^2\Delta_{21} \\ & - 8c_{13}^2 s_{13}^2 s_{23}^2 (1 - 2s_{13}^2) \frac{aL}{4E_\nu} \sin\Delta_{31} \left[\cos\Delta_{32} - \frac{\sin\Delta_{31}}{\Delta_{31}}\right] . \end{aligned}$$

Reactor and Accelerator Experiments

reactor ($\bar{\nu}_e$ disappearance)

$$P_{ee} \approx 1 - \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m_{31}{}^2 L}{4E_\nu}\right) - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\left(\frac{\Delta m_{21}{}^2 L}{4E_\nu}\right)$$

- Clean measurement of θ_{13}
- No matter effects

mass hierarchy

CP violation

matter

accelerator (ν_e appearance)

$$\begin{aligned} P(\nu_\mu \to \nu_e) &= 4c_{13}^2 s_{13}^2 s_{23}^2 \sin^2\Delta_{31} \\ &+ 8c_{13}^2 s_{13} s_{23} c_{23} s_{12} c_{12} \sin\Delta_{31}[\cos\Delta_{32}\cos\delta - \sin\Delta_{32}\sin\delta]\sin\Delta_{21} \\ &- 8c_{13}^2 s_{13}^2 s_{23}^2 s_{12}^2 \cos\Delta_{32}\sin\Delta_{31}\sin\Delta_{21} \\ &+ 4c_{13}^2 s_{12}^2[c_{12}^2 c_{23}^2 + s_{12}^2 s_{23}^2 s_{13}^2 - 2c_{12}c_{23}s_{12}s_{23}s_{13}\cos\delta]\sin^2\Delta_{21} \\ &- 8c_{13}^2 s_{13}^2 s_{23}^2(1-2s_{13}^2)\frac{aL}{4E_\nu}\sin\Delta_{31}\left[\cos\Delta_{32} - \frac{\sin\Delta_{31}}{\Delta_{31}}\right] . \end{aligned}$$

- $\sin^2 2\theta_{13}$ is missing key parameter for any measurement of δ_{CP}

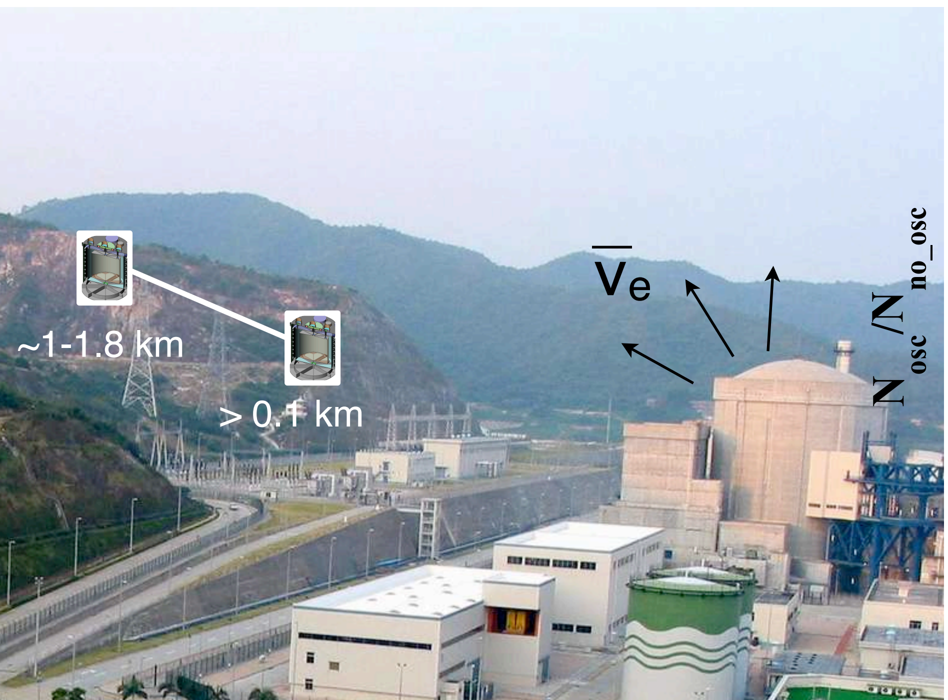
Precision Measurement of Mixing with Reactor $\overline{\nu}$

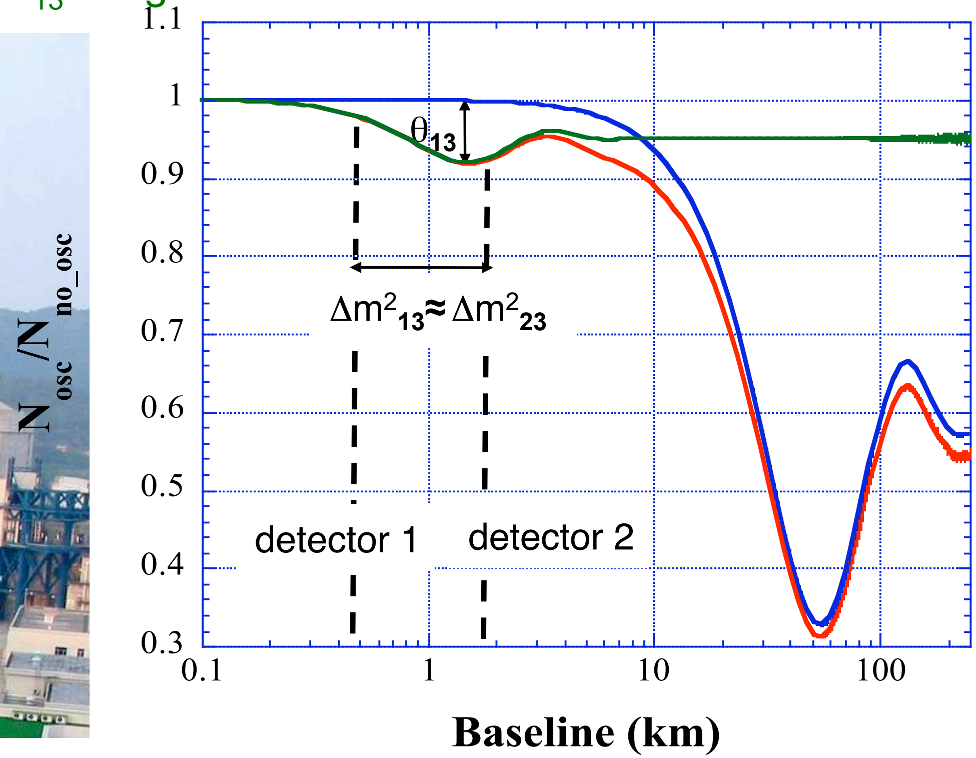
Search for θ_{13} in new oscillation experiment with multiple detectors

$$P_{ee} \approx 1 - \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m_{31}{}^2 L}{4E_\nu}\right) - \cos^4\theta_{13} \sin^2 2\theta_{12} \sin^2\left(\frac{\Delta m_{21}{}^2 L}{4E_\nu}\right)$$

Small-amplitude oscillation due to θ_{13} integrated over E

Large-amplitude oscillation due to θ_{12}





Reactor and Accelerator Experiments

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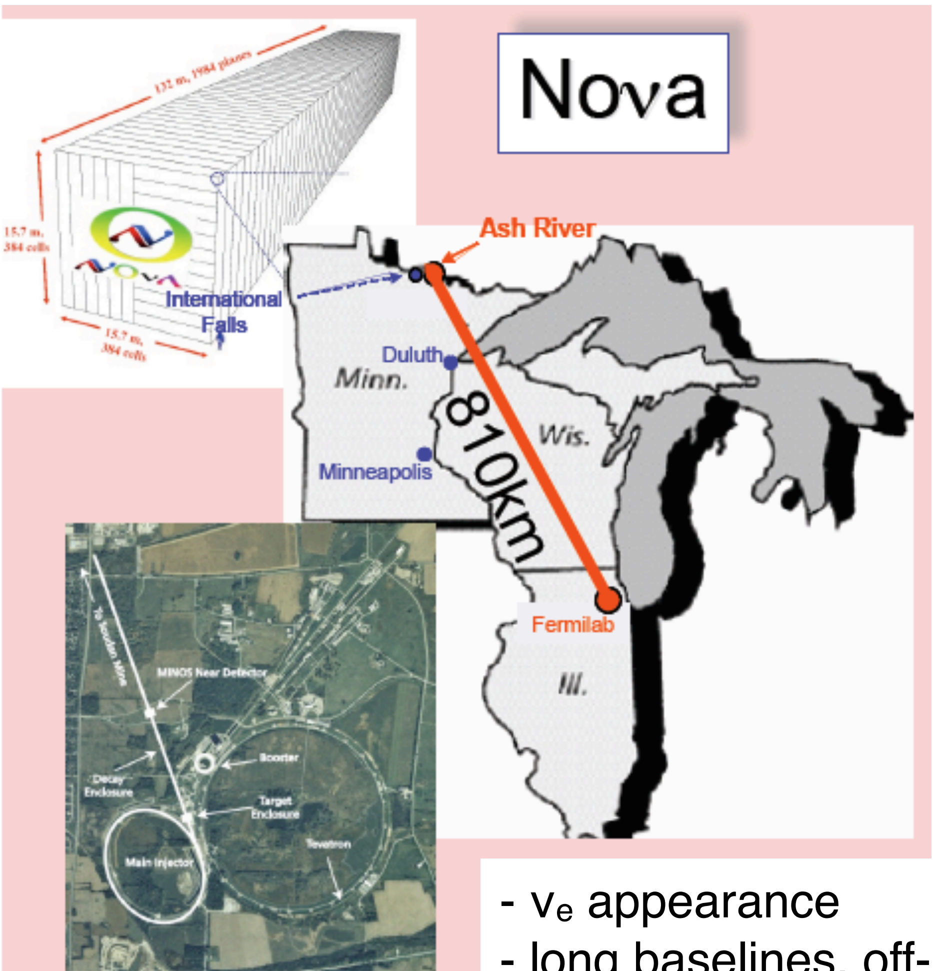
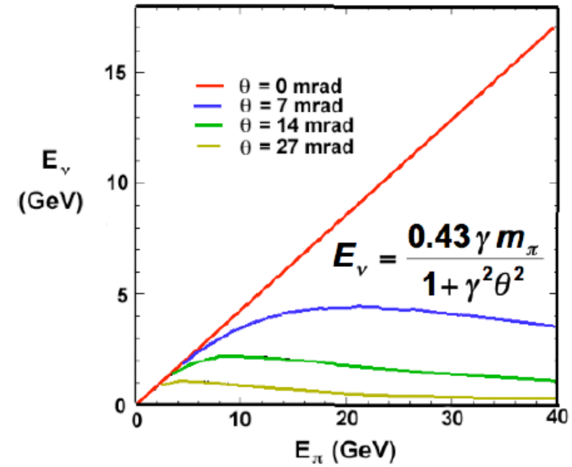
- $\sin^2 2\theta_{13}$ is missing key parameter for any measurement of δ_{CP}

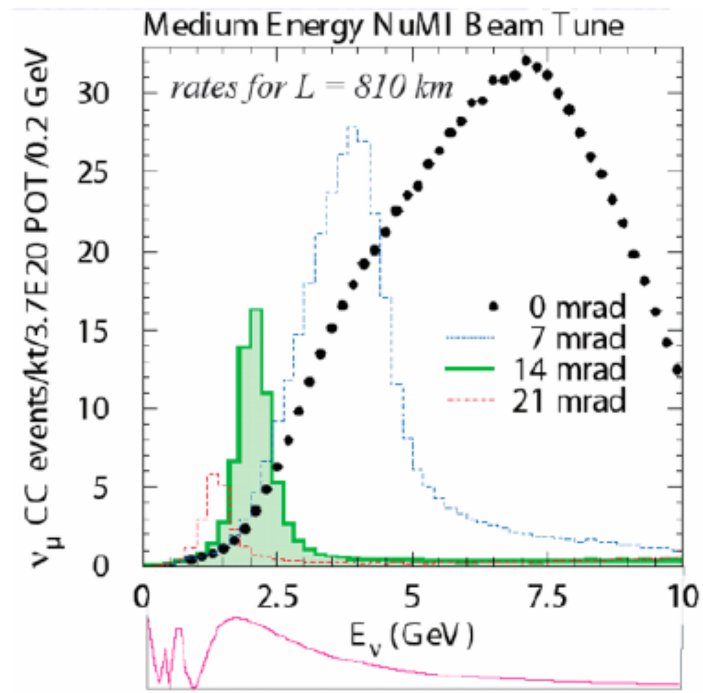
Accelerator Experiments (NOvA, T2K etc)

Long Baseline Accelerator Experiments



- ν_e appearance
- long baselines, off-axis
- matter effects



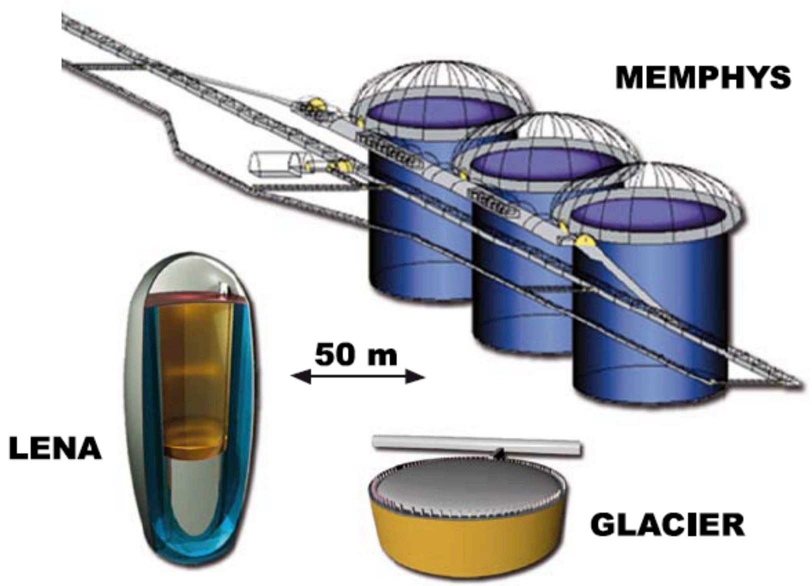


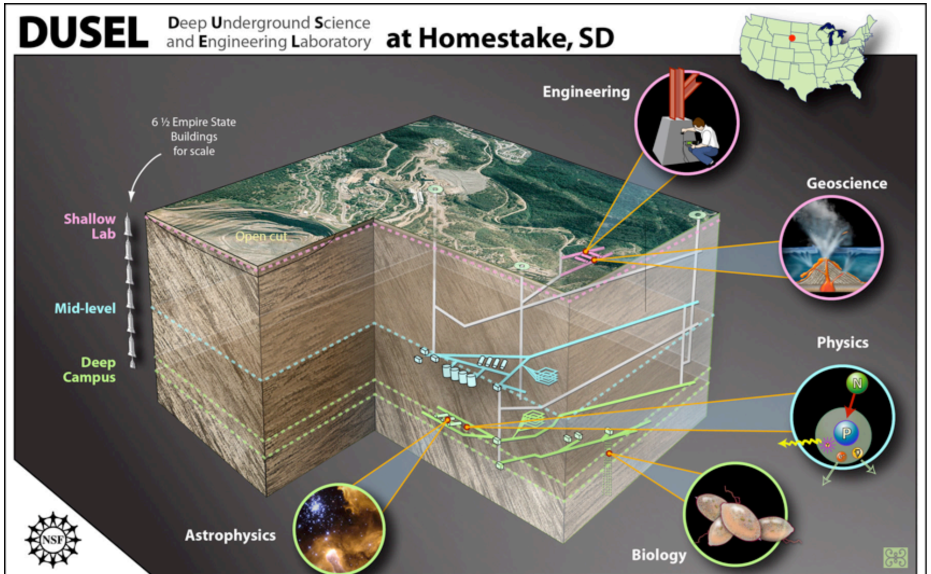
Future Neutrino Oscillation Experiments

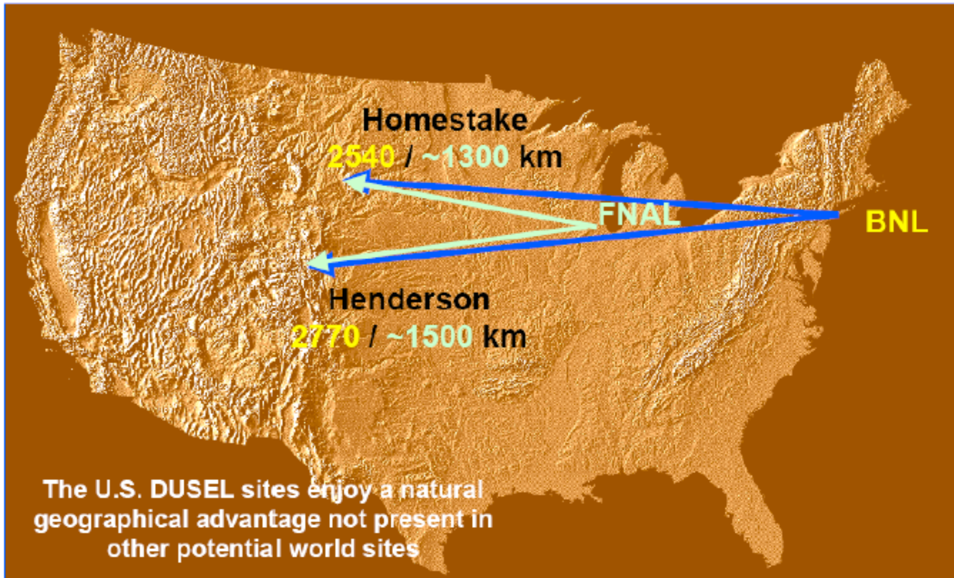
Large Detectors and Long Baselines

- search for CP violation with neutrino beam
- ν mass hierachy
- proton decay (10^{34} yrs→10^{35} yrs)
- astrophysics
- atm ν, geo ν

R&D in US, Europe, and Japan
Ultimate oscillation experiment by 2020?

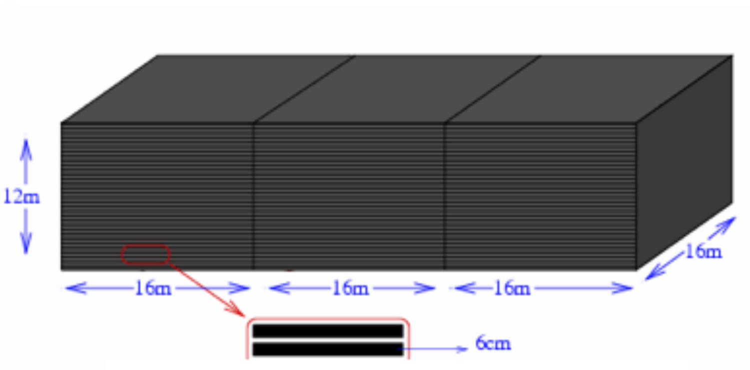






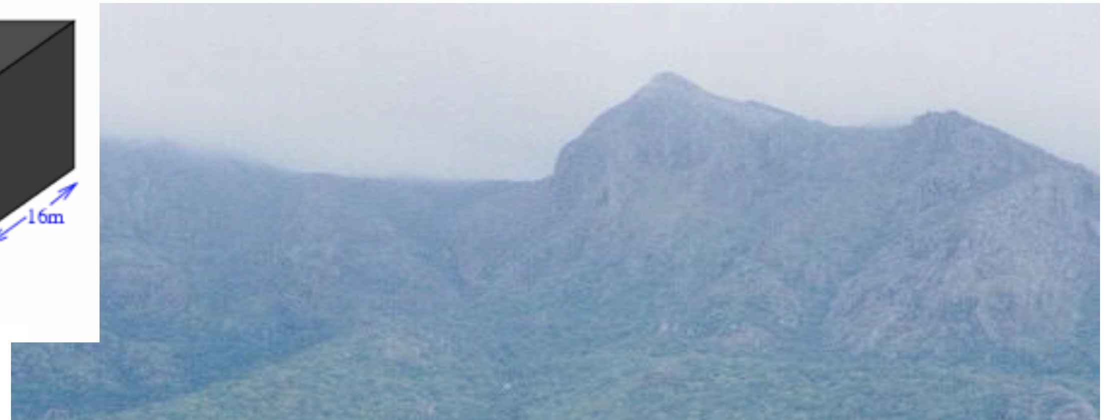
India Neutrino Observatory (INO)

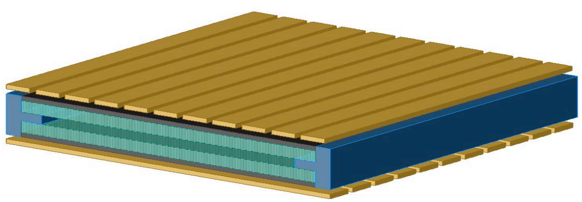
A Next-Generation Atmospheric Neutrino Experiment

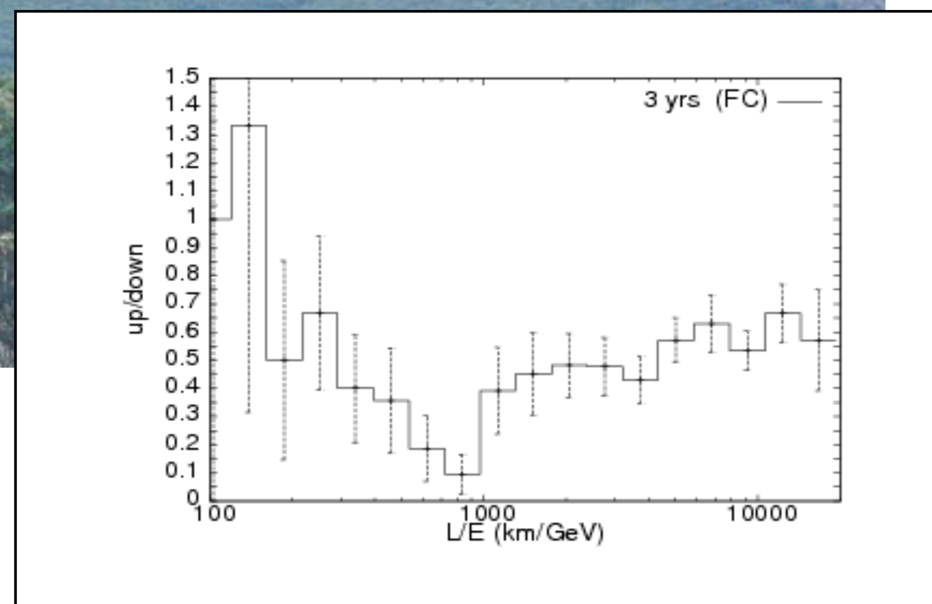


magnetized iron calorimeter

Magnetic field ~ 1 Tesla
along y-direction



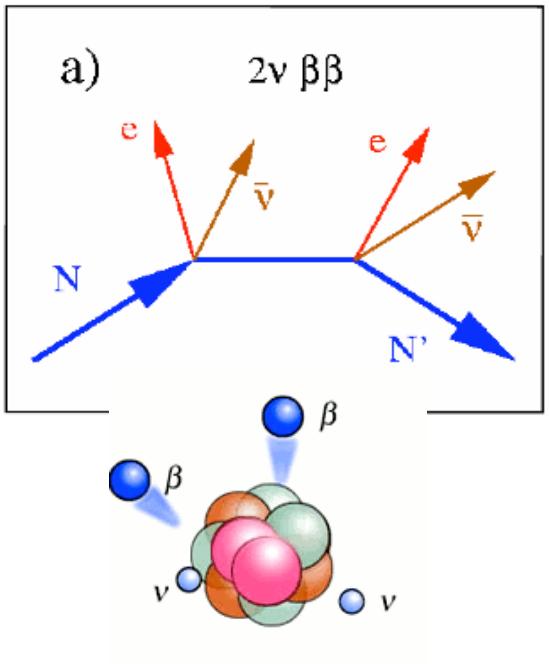


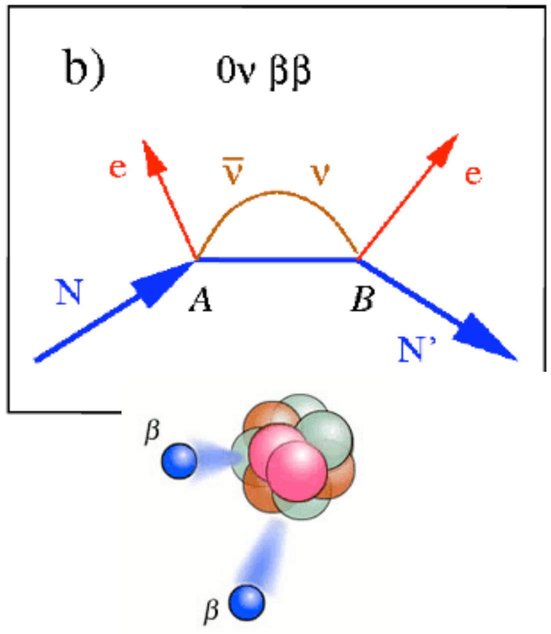


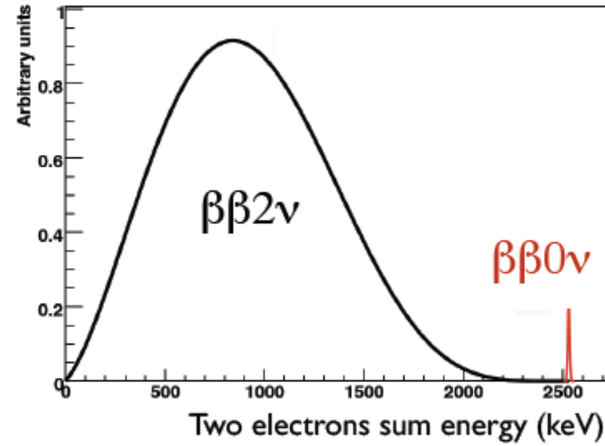
Mass: 50 kTon
Size : 48 m (x) ×16m (y) ×12 m (z)
140 layers of 6 cm thick iron
with 2.5 cm gap for active elements

Search for 0νββ

The Next Frontier in Neutrino Physics







search for 0νββ is the only feasible method we know to establish the Majorana nature of neutrinos!

2ν mode: conventional 2nd order process in nuclear physics

$$\Gamma_{2\nu} = G_{2\nu} \,|\, M_{2\nu} \,|^2$$

G are phase space factors

0ν mode: hypothetical process only if

$M_\nu \neq 0$ AND $\nu = \bar{\nu}$

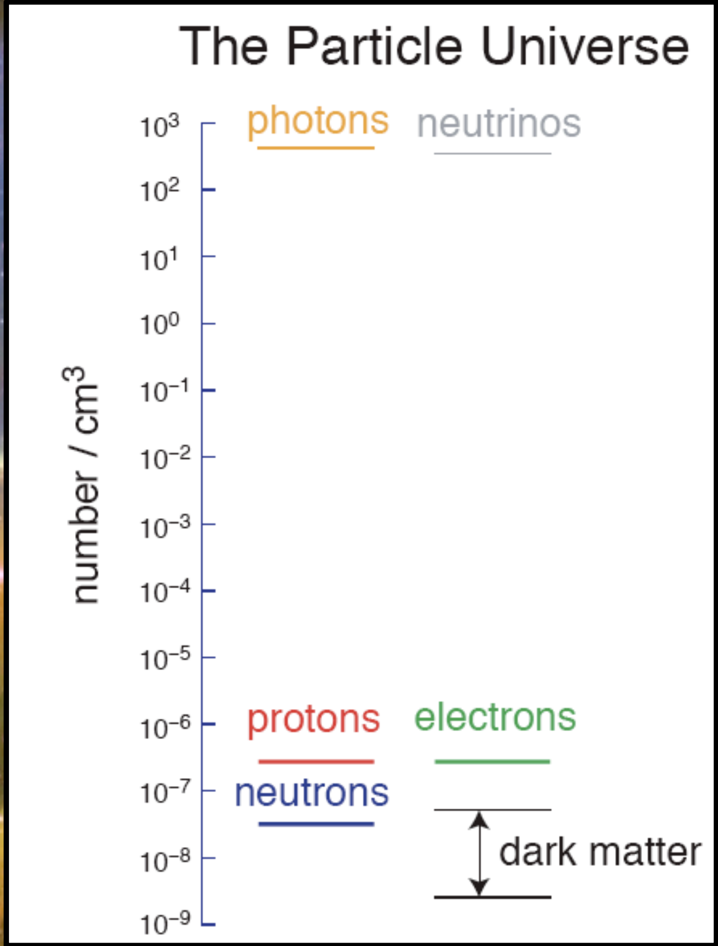
$$\Gamma_{0\nu} = G_{0\nu} \,|\, M_{0\nu} \,|^2 \langle m_{\beta\beta} \rangle^2$$

$G_{0\nu} \sim Q^5$

Neutrinos in the Universe

“neutrinos are the most abundant particles in the Universe besides photons”

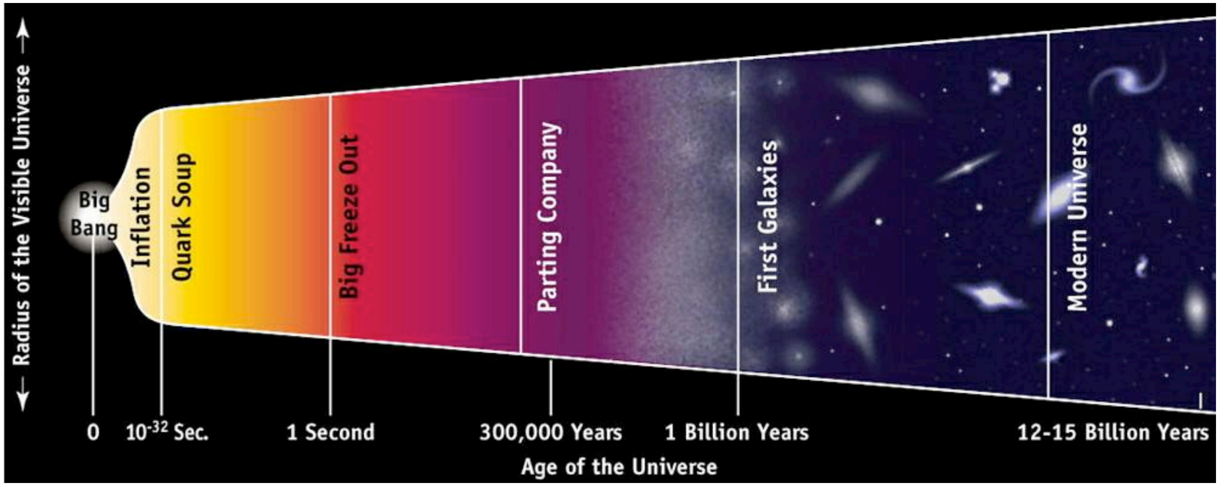
Neutrinos in the Universe

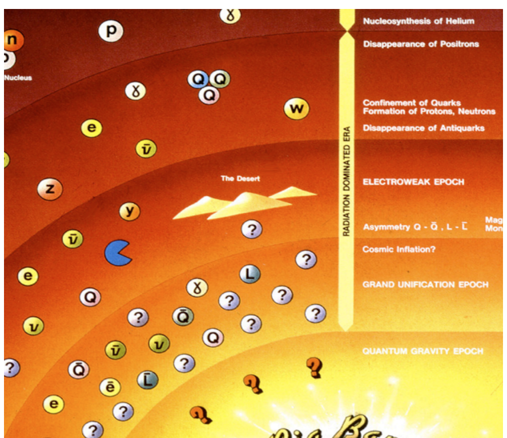


"neutrinos are the most abundant particles in the Universe besides photons"

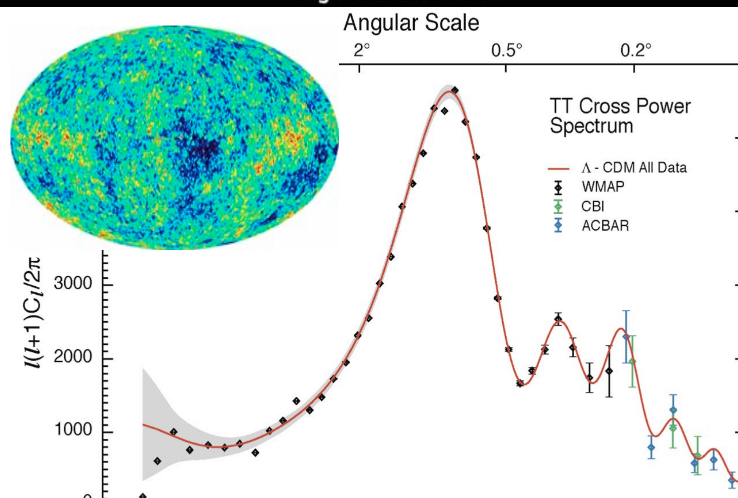
Neutrinos and the Universe

very early universe l big bang nucleosynthesis l CMB l late time structure formation

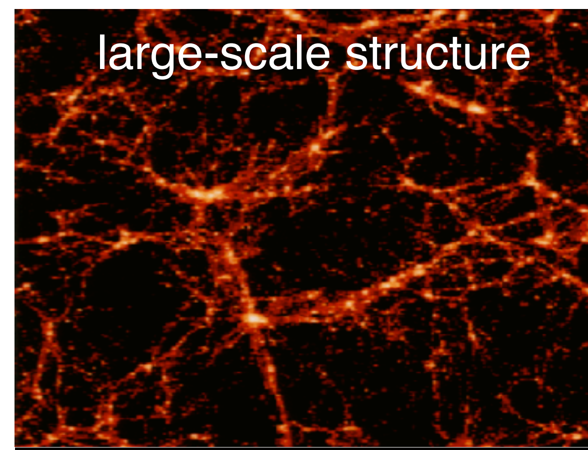




matter-antimatter ratio

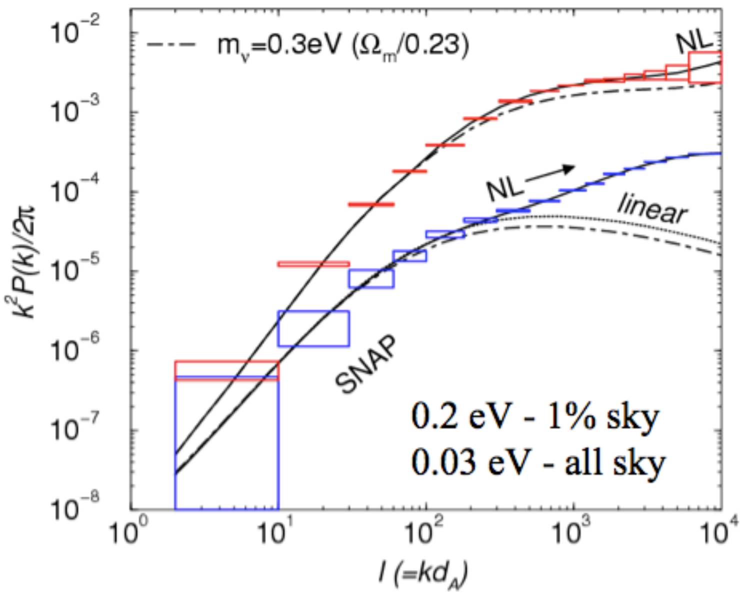


CMB



large-scale structure

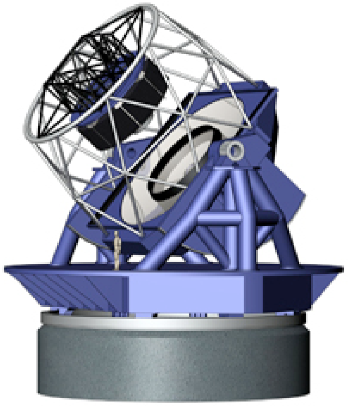
Future Cosmological Constraints on Σm_ν

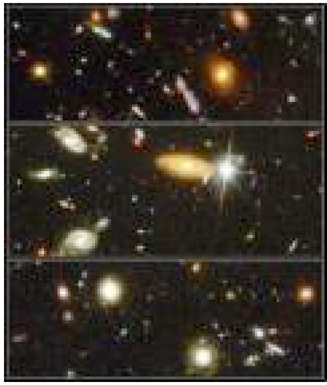


Cosmology probes important aspects of particle physics:

- Neutrino mass
- Dark energy equation of state

Partial degeneracy between m_ν, ω (neutrino mass states and dark energy equation)
→ cross-correlate CMB and LSS, weak lensing, BAO measurements





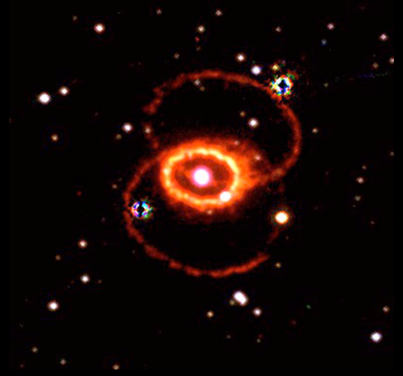
Model	Cosmological probes	$\sigma(\sum m_\nu)$
11 parameters	Planck only	0.48 eV
11 parameters	Planck+Wide-1	0.15 eV
11 parameters	Planck+Wide-5	0.043 eV
7 parameters	Planck+Wide-1	0.082 eV
7 parameters	Planck+Wide-5	0.037 eV

Ref: astr-ph/0603019

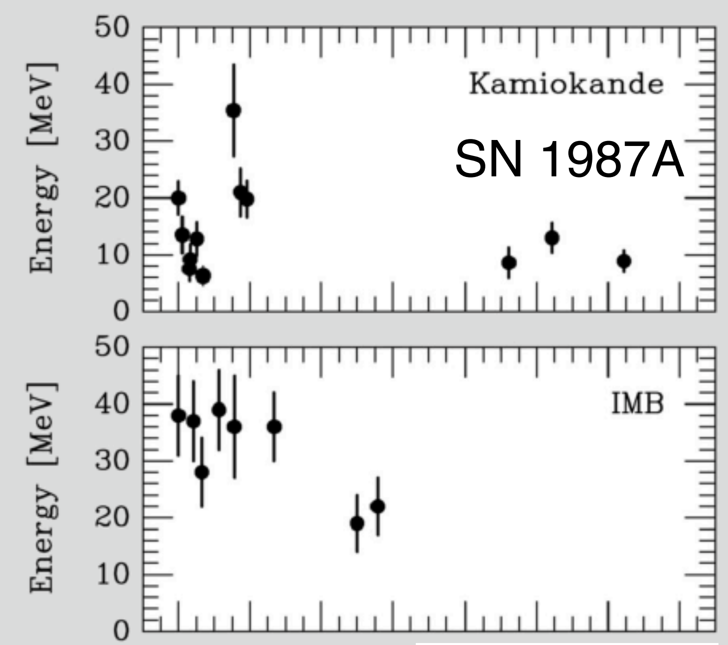
Planck + LSST-like lensing survey survey ⇒ **$\sigma(\Sigma m_\nu) \leq$ 0.05 eV**

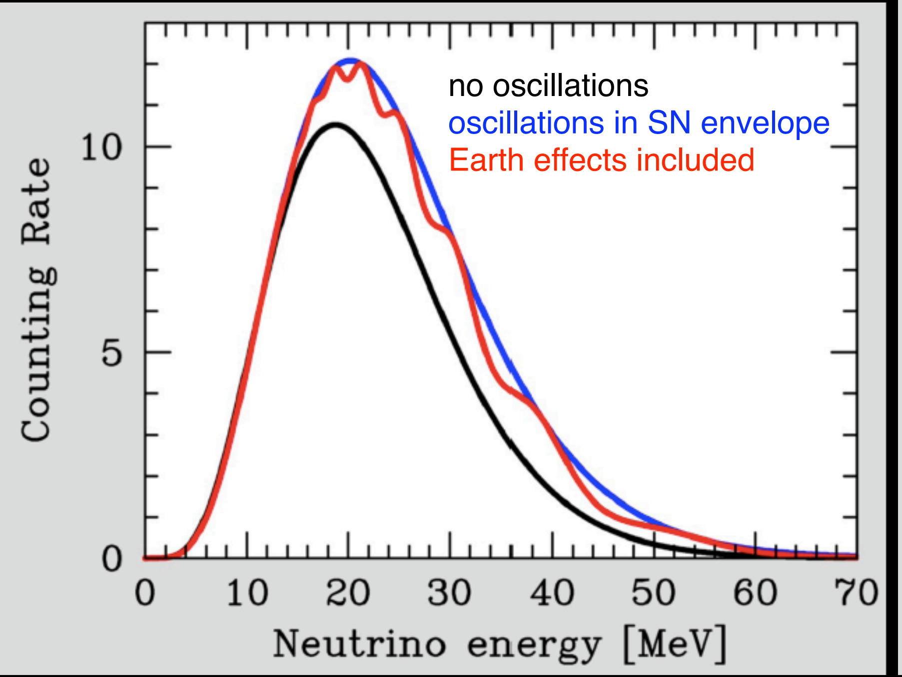
→ probes difference between normal and inverted hierarchy

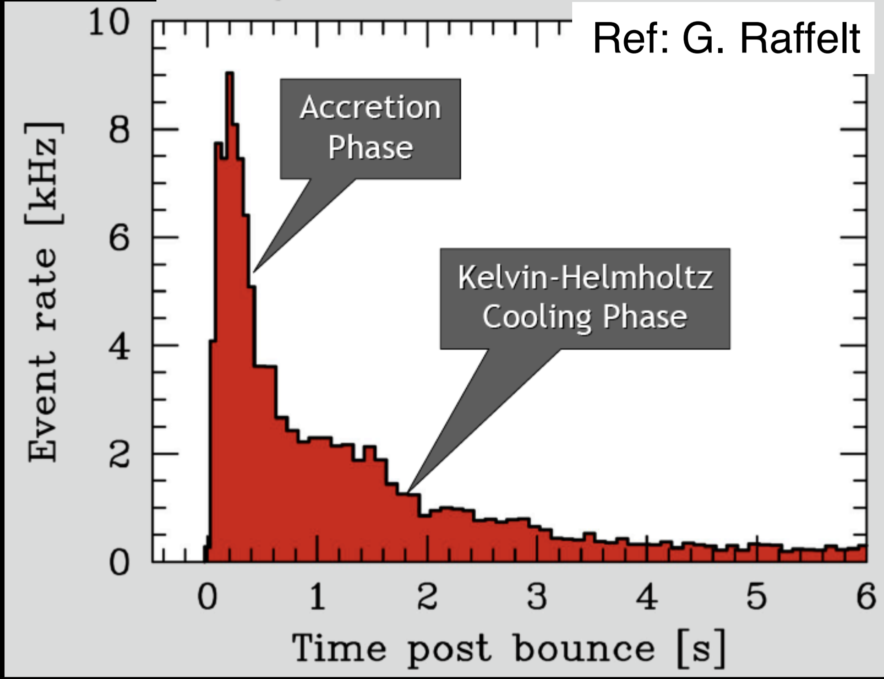
Neutrinos and Supernovae



"without neutrinos dying stars would not explode"

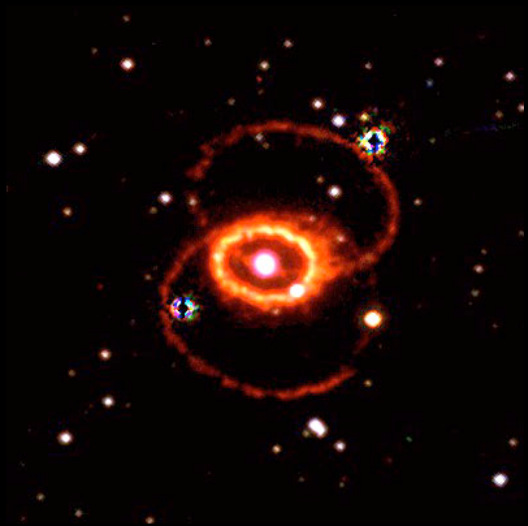




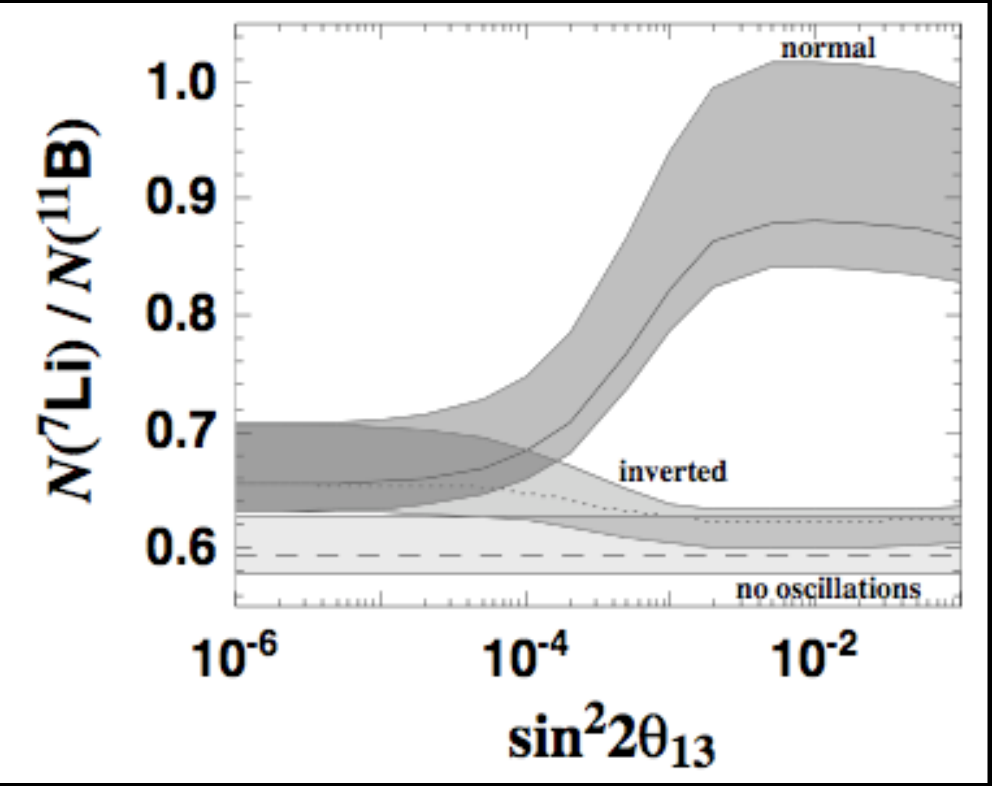


Ref: G. Raffelt

Neutrinos and Supernovae



neutrino oscillation effects on
supernova light-element synthesis



Astrophys.J.649:319-331,2006

“neutrinos helped cook the light elements in the Universe”

Interdependencies/Redundancies of Experiments

Need all types of experiments & observations

	absolute mass scale	Majorana Nature	Hierarchy	θ_{13}	δ_{CP}	α's
β-decay	✔					
0νββ -decay	✔	✔				✔
reactor				✔		
accelerator			✔	✔	✔	
atmospheric			(✔)			
astrophysics /cosmology	✔		(✔)	(✔)		

Some Concluding Thoughts

- Last 10 years have been the decade of discovery in neutrino physics. Neutrino physics has demonstrated physics beyond the Standard Model.

- Neutrino physics is transitioning from a discovery to a precision science. Reactor and accelerator experiments will play a critical role in precision studies (solar and atmospheric may help).

- A rich program of neutrino experiments is underway to understand neutrino properties.

- Neutrinos are important in many astrophysical processes, and astrophysics/cosmology may help us understand the particle nature of neutrinos